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A FURTHER STUDY OF CATION EFFECTS ON THE
PHYSICAL PROPERTIES OF CLAYS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
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by

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ABSTRACT

This thesis presents the effects of different adsorbed cations on some physical properties of a typical highly plastic Alberta clay. Homionic calcium, magnesium, sodium and potassium clays and samples of clay with varying quantities of sodium and calcium cations adsorbed, were produced. The natural clay was classified by standard tests which included cation exchange capacity and flame photometric determination of exchangeable cations. For the modified and natural soils, the Atterberg limits, shrinkage and swelling, permeability and consolidation characteristics were determined.

The calcium and magnesium cations did not appreciably alter any of the physical properties of the clay. The sodium cation caused large increases in plasticity, compressibility and swelling and substantially decreased permeability. The potassium cation decreased plasticity, compressibility and permeability and slightly increased swelling. The sodium cation, when adsorbed in varying quantities on a calcium clay, caused definite changes in the physical properties of the soil. With small additions of sodium, the compressibility, plasticity, amount of swelling and permeability decreased. Further additions of adsorbed sodium caused permeability to decrease further, and compressibility, plasticity and swelling gradually increased, approaching the values for an homionic sodium clay.

It is postulated that the cations may be divided into two groups depending upon their effects on the physical properties: flocculants, such as calcium and magnesium, and dispersants, such as sodium. The potassium cation exhibited characteristics of each group.

Recommendations for further research are included.

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GLOSSARY OF SYMBOLS

A_v	coefficient of compressibility
C_c	compressive index
C_v	coefficient of consolidation
E	strain
e	void ratio
k	coefficient of permeability
$me/100gms.$	milliequivalent per hundred grams of dry soil
mv	milli volt
S_{max}	maximum shear stress
S_d	dry transverse strength
$Tan B$	slope of line which expresses the relationship between the number of blows required to close the groove in the W_l device and the moisture content at that number of blows on a logarithmic plot
T_{max}	maximum torsional load at a constant
$\@ E^\circ$	rate of strain of 3 rpm.
$w\%$	moisture content expressed as a percentage of the dry weight of soil
W_l	liquid limit
W_p	plastic limit
W_s	shrinkage limit

GLOSSARY OF TERMS

Adsorb: Hold on a surface.

Amorphous: Having no determinate shape.

Anion: An ion carrying a negative charge of electricity.

Cation: An ion carrying a positive charge of electricity.

Cation Exchange Capacity: The quantity of cations that can be adsorbed and exchanged by a clay: it is considered to be a characteristic constant for a soil and is measured in milligram-equivivalents or milliequivalents of cation per 100 grams of dry soil.

Coefficient of Compressibility: The slope of the compression curve with void ratio as ordinate and applied pressure as abscissa.

Coefficient of Consolidation: A measure of the time rate of compression, equal to $\frac{1+e}{\gamma \omega A_v} k$.

Coefficient of Permeability: The constant of proportionality in Darcy's law relating velocity of flow to hydraulic gradient. May be broadly considered as the rate of flow of water through a unit area of soil under a unit hydraulic gradient.

Divalent Cation: An ion with a deficiency of two negative charges.

Dry Transverse Strength: A ceramics term used to designate the modulus of rupture of a standard clay bar.

Exchangeable Cation: An adsorbed cation that can be replaced by another cation.

Exfoliate: To come off in layers or scales.

Homionic Soil: A soil with only one type of cation adsorbed on its surfaces.

Ion: An atom or molecularly-bound group of atoms which have gained or lost one or more electrons and which thus has a negative or positive electrical charge.

Liquid Limit: The moisture content of a soil at the arbitrarily chosen boundary between the liquid and plastic states.

Micron: One thousandth of a milli-meter.

Milliequivalent: The amount of reagent required to combine or react with one milligram atomic weight of hydrogen. An equivalent is defined as 1.008 grams of hydrogen, and the milliequivalent is 1/1000 th of an equivalent.

Plastic Index: The difference between the liquid limit and the plastic limit.

Plastic Limit: The moisture content of a soil at the boundary between the plastic and semi-solid states.

Shrinkage Limit: The moisture content of a soil when saturated and at the minimum volume it can attain by drying.

Soil Solution Ratio: Ratio of dry weight of soil in grams to volume of solution in cubic centimeters.

Supernatant Liquid: The clear liquid that remains when a colloid or suspension settles to the bottom of the container.

Van der Waal's Forces: Forces acting between all units of matter resulting from the mutual influence of electronic motion between atoms.

Void Ratio: The ratio of the volume of voids to the volume of solids in a soil.

Water of Plasticity: A ceramics term used to define the moisture content required to produce a certain degree of workability in a clay.

Zeta Potential: The difference between the potential of the immovable layer attached to the surface of the solid phase and the moveable liquid layer in the body of the liquid.

FOR E W O R D

In the fall of 1961, P.A. Thomson presented to the Faculty of Graduate Studies at the University of Alberta a thesis entitled "The Effects of Exchangeable Cations on Some Properties of Clay Shales". As a result of his work, it was decided that further research on this subject was warranted as many questions regarding the effect of cation exchange on soil properties remained unanswered. This present investigation was carried out as a "follow-up" to Thomson's work in an effort to expand and elaborate on his findings.

INTRODUCTION1.1 Some General Applications of Ion Exchange

The phenomenon of ion exchange was first systematically studied by Thompson in 1850. Later in the nineteenth century, Way showed that cation exchange in soils was restricted mainly to the clay fraction and that it was connected with the silicate compounds in the soil. Through his work, it was concluded that the replacement of cations adsorbed on the clay particles with different cations from the soil pore solution could markedly change the properties of a soil. Since then, much work on this subject has been carried out by agronomists, physical chemists, geologists, chemists and workers in the ceramics industry (Kelly, 1955),* and recently by engineers in the field of soil mechanics.

Agriculturalists have long been aware of the fact that fertilizer applied to a soil will make it more productive. According to Shawarbi (1952), the increase in productivity is the end result of an ion exchange reaction which occurs between the soil particles and the pore water and which causes displacement of mineral base elements from the soil particles. These displaced particles enrich the soil-water solution.

* References are indicated by author and year of publication and are listed in the bibliography at the end of this report.

The zeolite* water softening process is another example of ion exchange. Calcium bicarbonate in many water sources reacts with soap to form an insoluble curd which is useless for washing. In the softening process, calcium cations are replaced by sodium cations which form a soluble salt and a curd is not produced.

Sullivan and Graham, as cited by Coates (1954), investigated the effects of the exchangeable cation on the strength and workability of pottery clays. They found that these properties could be altered substantially and to advantage by promoting cation exchange.

Some geologists consider that ion exchange is an active factor in the production of clay size particles by weathering of the parent material. Fredrickson (1951), proposes, largely on theoretical grounds, that the mechanism of weathering is essentially a base exchange or ion exchange process. He theorized that hydrogen ions are exchanged for metallic ions in the parent material and a net expansion in the reacting layer of the rock crystal results. The expansion causes the rock to exfoliate producing smaller fragments, resulting in a net increase in specific area and hence, an increase in chemical activity.

1.2 Cation Exchange and the Physical Properties of Soil

Although the importance of ion exchange effects on various pro-

* Zeolites are complex sodium aluminosilicates which exhibit the property of exchanging their sodium ions for calcium or magnesium ions in solution.

properties of soils has been recognized for approximately one hundred years by workers in other fields, workers in the field of soil mechanics did not investigate the cation exchange effects on the engineering properties of soil until approximately twenty years ago.

Engineers have recognized for some time that many clay soils, having identical grain size distributions may have greatly differing physical properties. These differences are due mainly to the variation in the crystal structure of the various clay types, which in turn, affects the adsorbed water and the quantity of adsorbed ions on the soil particle. The physical properties of soil, such as plasticity, shrinkage, swelling and compressibility depend to a great extent on the thickness of the adsorbed water films and on the type and quantity of adsorbed ions. Grim (1952) states, "A fundamental understanding of the properties of soil cannot be attained without considering ion exchange."

1.3 Importance of Cation Exchange

There are three main reasons why engineers working with soils should be interested in ion exchange.

Firstly, as previously stated, one must have a knowledge of the mechanism and results of ion exchange on soil in order to fully comprehend the behaviour of soils.

Secondly, in some cases it is possible to improve soil for engineering purposes by means of promoting cation exchange. Base course

stabilization by the addition of lime is a process whereby the exchangeable cations on the soil are replaced by calcium cations. Coates (1954) states, "Experimental work has shown that in some soils, swelling due to frost action can be dramatically reduced by changing the exchangeable cation. Other work indicates that the bearing capacity of piles may be increased by promoting cation exchange. At the Golden Gate Exposition, the permeability of a lagoon was reduced by 90% as the result of cation exchange. Some work suggests that the strength of clays may be altered by cation exchange."

Thirdly, the exchangeable cation on the soil not only influences the physical properties of the soil, but also affects the ability of the soil to react with other substances. It is known to influence the reaction with portland cement in cement stabilized roads (Grim 1952).

Hence, it can be seen that cation exchange has potentially a wide range of practical applications. To date, however, its use has been restricted to base course stabilization and to improvement of permeability characteristics. In both applications, only a thin layer of the surface soil is treated.

One of the major obstacles to be overcome before cation exchange can be used extensively to improve the bearing capacity of soils or the stability of slopes, is the difficulty of injecting or treating the entire volume of the trouble-some soils "in situ". The characteristic low perm-

eability of the soil mass prevents adequate dispersion of the solution throughout a relatively large volume of the soil.

1.4 Purposes of the Investigation

The purposes of this investigation were:

- a) To determine a satisfactory laboratory procedure with which homionic soils could be produced.
- b) To determine the effects of various cations on some of the physical properties of a typical highly plastic clay from the Edmonton Region.
- c) To determine the effects of the Na^+ cation in varying quantities on the physical properties of a homionic Ca^{++} clay.

In order to obtain results which are indicative of the changes in soil properties that are brought about by changing the adsorbed cations on the soil, it is necessary that homionic modifications of the soil be produced. If it is desired to determine the effect of, say, the Ca^{++} cation on the engineering properties of soil, then the soil must contain only adsorbed Ca^{++} cations. If other cations are present, even in small quantities, they may exert magnifying or suppressing effects on the physical properties. Winterkorn (1953) states that for montmorillonite, if as little as 15% of the exchangeable cations are Na^+ , then the soil will behave as an homionic Na^+ soil.

Previous workers in this field, such as Coates (1954), Thomson (1960) and others, experienced difficulty in producing homionic soils. Coates

did not analyse his modified soils to determine whether homionic soils had been achieved. Flame photometer tests conducted by Thomson on his modified soils showed that they were not homionic. Both workers used the same technique to produce their modified soils and hence it can be assumed that Coates did not achieve homionic modification.

Coates found that Na had a suppressing effect on the liquid limit while Thomson and others found that Na caused an increase in the liquid limit. It is felt that these differences could be due to the presence of small amounts of extraneous cations in the so-called homionic soils produced.

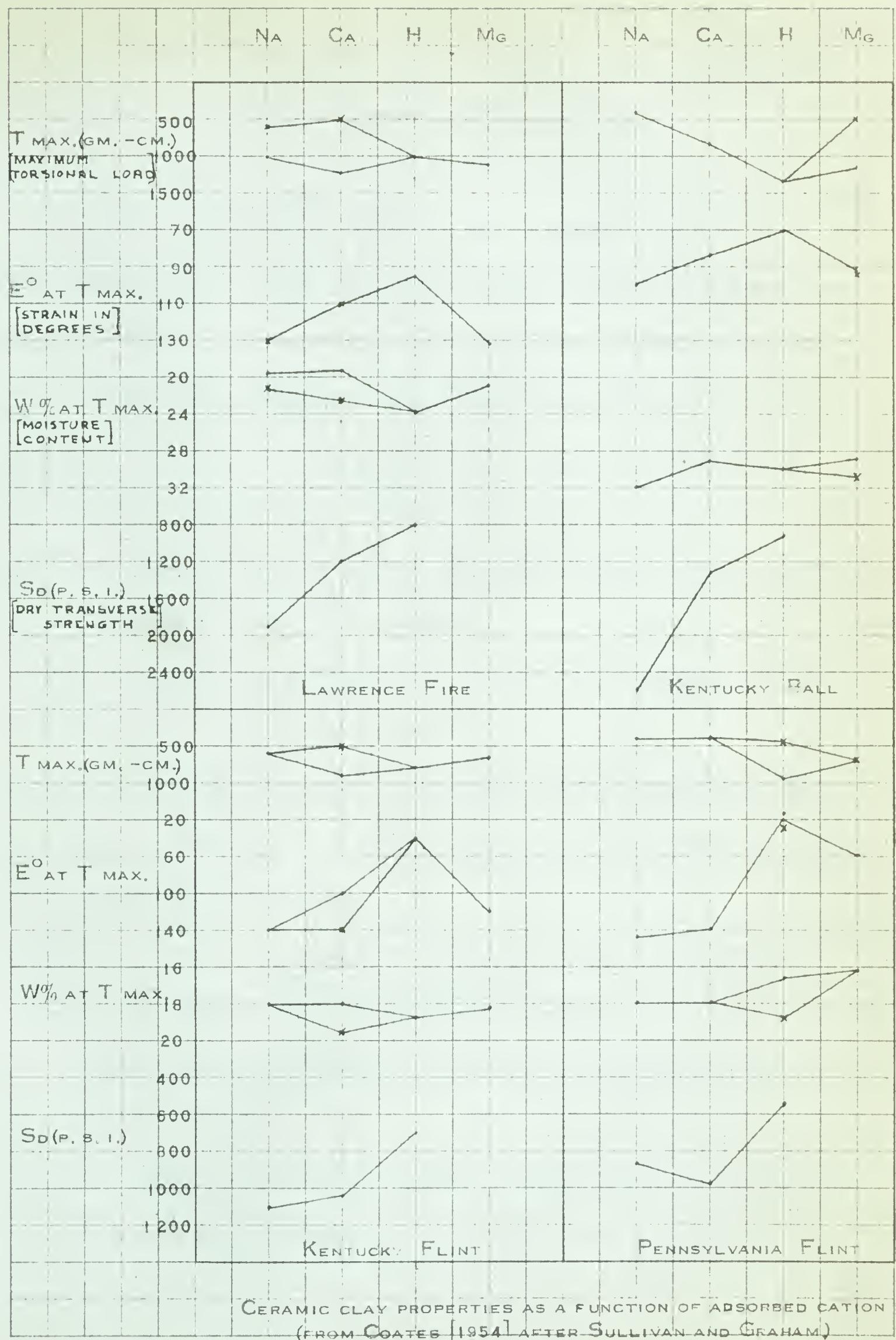
Because of the conflicting results of these workers and others, it was felt that further research on this subject was warranted.

CHAPTER 2

PREVIOUS RESEARCH ON CATION EXCHANGE AND
ITS INFLUENCE ON THE PHYSICAL PROPERTIES
OF CLAY

Until approximately twenty years ago, very little research had been undertaken to determine the effects of the exchangeable cations on the physical or engineering properties of clay. However, it has been definitely established by such workers as Sullivan (1940), Winterkorn (1941), Coates (1954), Lambe (1954), Mielenz (1955) and Baver (1956), that the type and quantity of adsorb cations affect such physical properties of the soil as plasticity, shrinkage, swelling permeability, shearing strength, and consolidation.

Sullivan and Graham (1940), cited by Coates (1954), investigated the effects of cation exchange on the wet strength of various clays used in the ceramics industry in the United States. Unfortunately, since the samples were tested at greatly varying moisture contents, and, since a change in the shearing strength of a clay can be caused by a change in moisture content, it was not possible to differentiate between those strength changes caused by ion exchange and those caused by a change in moisture content. Different types of clays were treated chemically, yielding modifications which had Na, Mg, K and H as the adsorbed cations. The investigation indicated that the shearing strength of clays might increase with an increase in valence of the adsorbed cation. Further, the strain at failure was found to increase with an increase in valence of the adsorbed cation. (see plate 1)

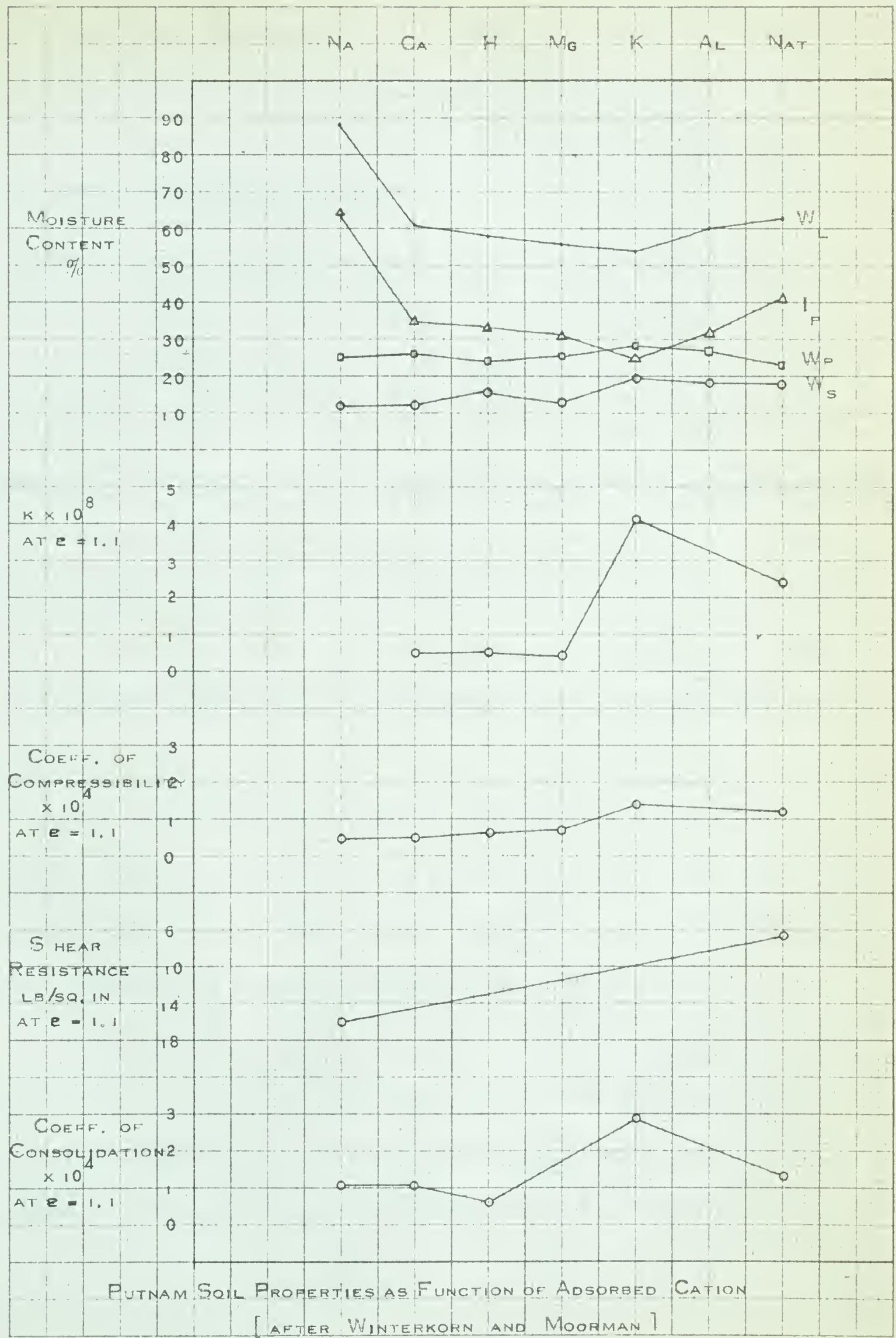


Sullivan and Graham also investigated the effects of cation exchange on the dry transverse strength of clays. It was concluded that the dry strength of Na-clay was greater than that of Ca-clay.
(see plate 1)

Winterkorn and Moorman (1941) made a detailed study of the effects of exchangeable cations on the physical properties of Putnam clay (beidellite). Homionic variations of Ca, K, Na, Mg, and Al - Putnam soil were created and engineering tests were performed on each of the modifications. Some of the results of this investigation are shown on plate 2. Definite changes in the physical properties occurred with changes in the type of adsorbed cation. From the results of their investigation, Winterkorn and Moorman concluded:

"

1. The engineering properties of a soil can be radically altered through change of the adsorbed ions.
2. The physical properties of a cohesive soil are dependant upon the structure and character of the water films surrounding the solid soil constituents.
3. The water film structure is determined by the intensity and the extension in space of the force fields about the adsorbed ions and their interrelation with the force fields of the solid soil particles.
4. Variations in the shear and consolidation behaviour of homionic soils containing intermediate amounts of moisture can be pic-



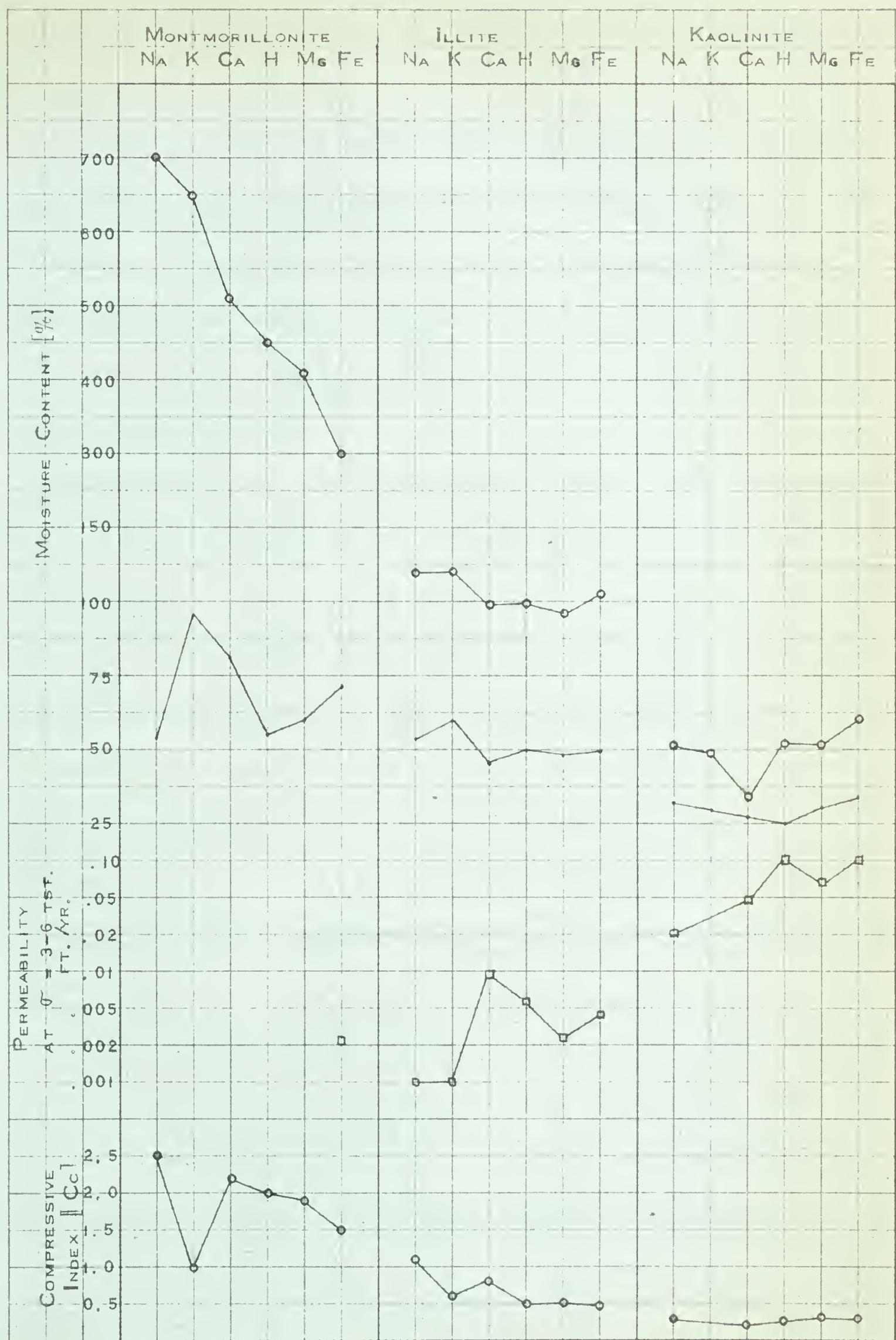
tured as due to changes, caused by the ions, in the viscosity of the adsorbed water films.

5. The Atterberg Tests furnish evidence of the water film structure which can be used in predicting trends of other engineering properties of soil."

From 1946 to 1951 an extensive investigation of the basic clay properties was carried out at Cornell University, and the results of that portion of the research programme which dealt with cation exchange were tabulated by Coates (1954) (see plate 3). Again no general trend was evident except that the liquid limit and the plastic limit showed a tendency to decrease with an increase in the valency of the adsorbed cation. Of the three types of soil investigated, i.e., montmorillonite, illite and kaolinite, the modified montmorillonite showed the greatest variation in liquid limit ranging from over 700% for Na - montmorillonite to just under 300% for Fe - montmorillonite.

Coates (1954) conducted a study to determine the effects of the exchangeable cations on the engineering properties of Leda clay. This clay was deposited after the last retreat of the Pleistocene ice sheet and is found in the St. Lawrence and Ottawa River valleys in eastern Canada.

The original clay was first transformed into an H-clay by treatment with H Cl and the H-clay in turn was converted into Na-clay and Mg-clay by treating with MgO and NaOH. No tests were performed on the resulting modifications to determine if true homionic soils were produced by this



CLAY MINERAL PROPERTIES AS A FUNCTION OF THE ADSORBED CATION
 [FROM COATES [1954] AFTER CORNELL UNIVERSITY]

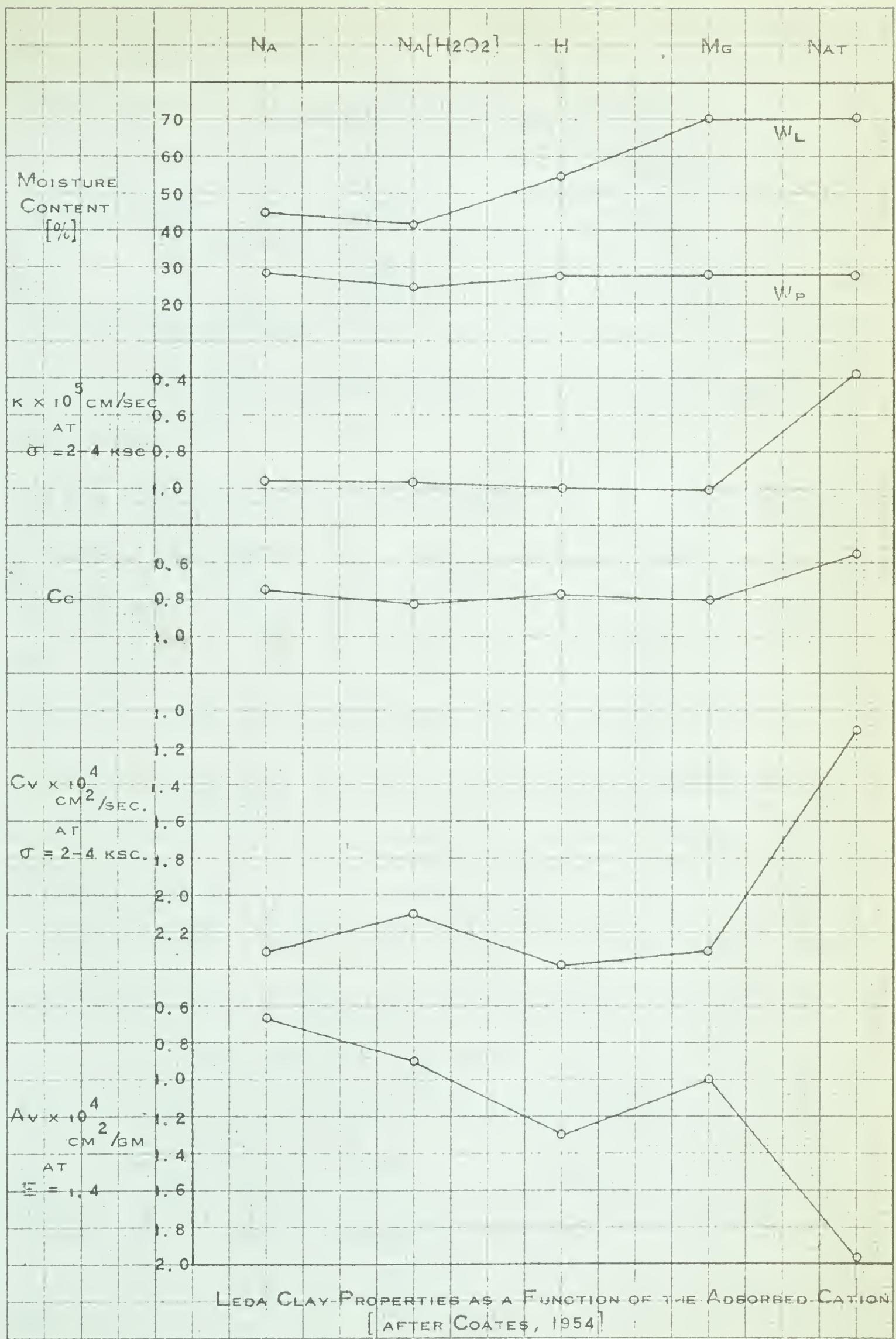
method. The results of this investigation are shown on plate 4.

Davidson and Scheeler (1952) conducted a study on the cation exchange capacity of Wisconsin loess.

It was shown that the amount of 0.002 m. m. clay, the liquid limit, the plasticity index and the hygroscopic moisture increased with an increase in cation exchange capacity. The plastic limit and the shrinkage limit decreased with an increase in cation exchange capacity. It was also shown that the presence of carbonates in loess tends to lower the cation exchange capacity of the soil.

Matsuo (1957) investigated a landslide at Kashio, Japan. He reasoned that the slide was triggered by the action of ground water percolating through the slope and removing calcium from the soil through an ion exchange process. A chemical analysis was made of rainwater and of ground water from the foot of the slide area which indicated that the ground water and the rainwater were essentially of the same chemical composition, except for the quantity of Ca^{++} cations in each. It was found that the amount of Ca^{++} in the rainwater was 0.07 m. e. per liter (milliequivalents per liter), while the ground water contained 1.13 m. e. per liter.

Matsuo reasoned that this increase was due to cation exchange and was of the opinion that previously the soil had been calcium saturated. Tests indicated, that at the time of the slope failure, only 3/4 of the exchangeable cations on the soil were calcium. Shear strength tests were



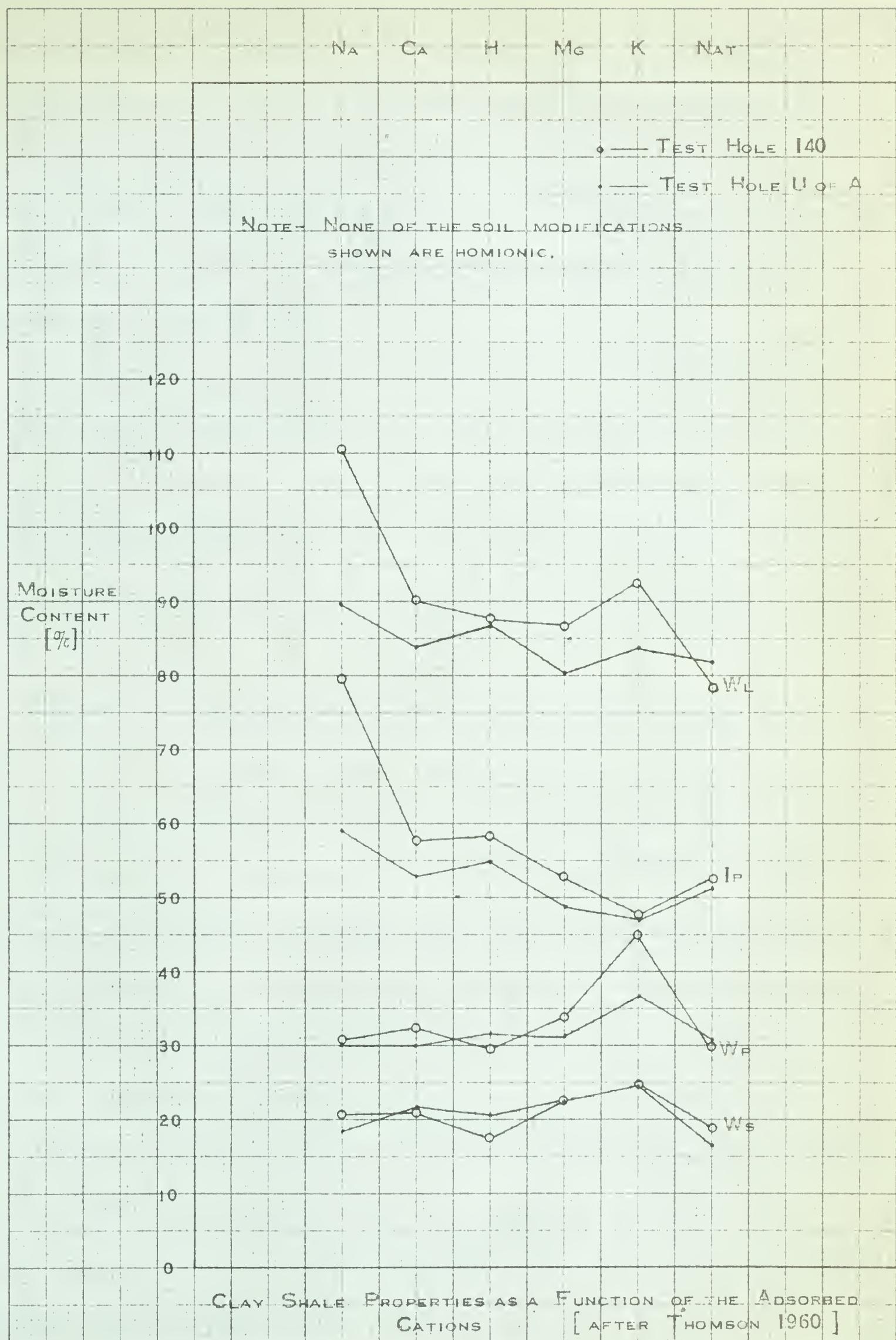
performed on the natural soil and on a calcium saturated soil. The following results were obtained:

natural soil	-- friction angle	=	0.06 $^{\circ}$
	cohesion	=	0.08 kg/cm ²
calcium soil	-- friction angle	=	0.45 $^{\circ}$
	cohesion	=	0.163 kg/cm ²

Stability computations based on these values showed that the factor of safety of the Ca^{++} soil was 1.3, while the factor of safety of the natural soil was only 0.6.

It was concluded that the initially stable Ca^{++} -- saturated soil had been altered by means of cation exchange, and that a reduction in shear strength occurred, which led to failure of the slope. It was also suggested that the stability of such slopes could be maintained by injecting aqueous solutions of calcium salt at the top of the slope.

Thomson (1960) found that the physical properties of Northern Alberta clay shales are changed by changing the adsorbed cations. The natural soil was altered to produce modified soils in which the dominant cations were Na^+ , K^+ , Mg^{++} , Ca^{++} and H^+ . Homionic modifications were not achieved. His Atterberg Limit test results are shown on plate 5. Consolidation tests were also performed on remoulded samples of each of the modified soils. From these tests, the compressive index and permeability of each sample was calculated. It was found that the type of adsorbed cation had little or no effect on the compressive index of the soil.



It was also shown that the adsorbed cation appreciably affected the permeability of the soil. The Na^+ modified soil was approximately seven times less permeable than the natural soil, while the K^+ ion caused the permeability to increase to more than double that of the natural soil.

The Mg^{++} and H^+ modifications were found to be slightly more permeable than the natural soil, while the Ca^{++} modified soils were about twice as permeable as the natural soil.

A review of the previous paragraphs shows that no definite trend between the plasticity characteristics of soils and the type of adsorbed cation has been arrived at to date. Some workers (Winterkorn, Moorman Thompson) indicate that the Na^+ cation produces the highest WL and largest PI, while other workers (Coates and Cornell University) do not agree with this.

It has been definitely established that the Na^+ soil has low permeability, high swelling and shrinkage characteristics and that Ca^{++} soil does not swell appreciably, is little affected by shrinkage and is very permeable.

To summarize, previous work has shown that the type of cation adsorbed on a soil appreciably affects such characteristics as plasticity, shrinkage, swelling, permeability and consolidation. However, the magnitude of the effect of each cation on these properties has not been satisfactorily established and various workers show conflicting results.

Winterkorn has shown that if as little as 15% of the exchange cations on a soil are Na^+ then the soil will behave as an homionic soil. Producing homionic soils in quantity is a difficult task and it is felt that soils produced by some of the early investigators were not homionic.

In only one of the investigations outlined previously in this chapter, was there any evidence shown that an analysis of the modified soils was made to determine if these soils were homionic. Thomson (1960) analyzed his modified soils by flame photometer tests and the results show that they were far from being homionic. The conflicting results are possibly due to the presence of small quantities of extraneous cations in the so-called homionic soils which may cause suppressing or magnifying effects on the physical properties.

CHAPTER 3

THE NATURE OF CLAY

3.1 Definition of Clay

Clay may be defined as an aggregate of microscopic and sub-microscopic particles derived from the chemical decomposition of rock constituents (Terzaghi 1948). A clay soil, as defined by the engineer, is composed predominantly of particles smaller than two microns in diameter and exhibits plastic characteristics.

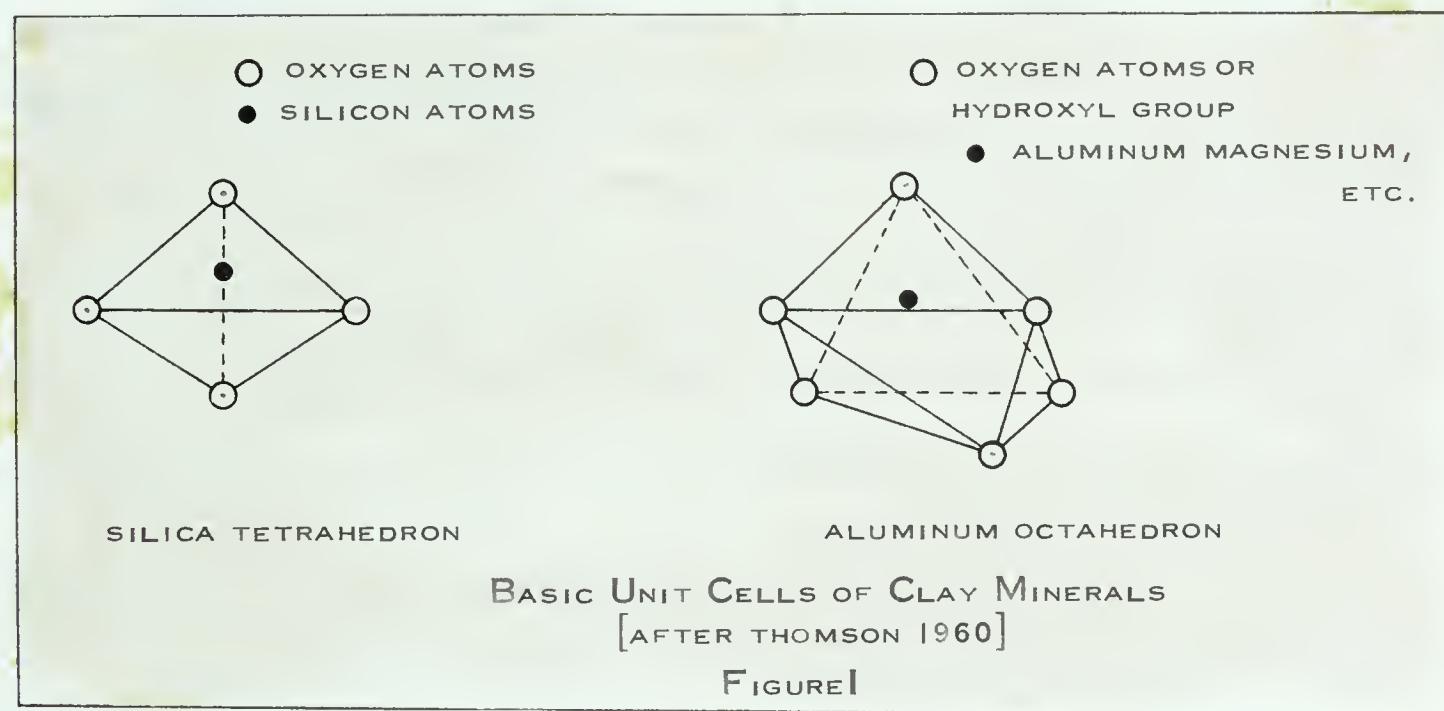
Below about 0.2 microns in diameter, the clay minerals behave as a colloid and hence the term colloidal clay was developed. Clay minerals can occur in particles as small as 0.1 milli-micron, approaching the dimension of the unit cell (Mielenz 1955).

3.2 Basic Unit Cells of Clay

Bauer (1956) and other has established in the last few years that clay minerals are crystalline in form and that four main constituents -- silica, alumina, iron and combined water make up 90% - 98% of colloidal clay. A crystal is a regular grouping of ions or molecules resulting in the greatest possible degree of electrical neutralization and the unit cell is the most elementary grouping. For clays there are two basic unit cells -- the silicon-oxygen tetrahedral and the aluminum-hydroxyl octahedron. The alumina unit consists of two sheets of closely packed oxygen atoms or hydroxyl groups which are held together by aluminum atoms in

such a way that one aluminum is surrounded by six oxygen atoms or hydroxyl groups, three from each sheet. The silica unit consists of a sheet of oxygen atoms held together by silicon atoms so that the silicon atoms are surrounded by four oxygen atoms, three in the sheet and one above. The oxygen atom above the sheet provides the means for linking a silica unit to an alumina as it can serve as one of the oxygen atoms which surround the aluminum in the alumina sheet (Bauer 1956).

(see figure 1)



3.3 Types of Clay Minerals

Thomson (1960) lists five groups of clay minerals:

- (1) The Kaolin group with 1:1 lattice type
- (2) The Hydrated mica group with 2:1 lattice type
- (3) The Montmorillonite or expanding lattice group with a 2:1 lattice type
- (4) The Fibrous clay group

(5) The Regular Mixed Layer group as described by Grim (1953)

The 1:1 lattice type and the 2:1 lattice type refers to the stacking of the basic unit cells of the clay mineral. In the Kaolins, silicon tetrahedron layers alternate with aluminum octahedron layers. The Hydrated Mica group with 2:1 lattice type has one aluminum octahedron layer between two layers of silica tetrahedrons. The Montmorillonite group with 2:1 lattice type has two silica tetrahedron sheets, one above and one below each aluminum octahedron sheet.

Minerals of the Kaolin group include Kaolinite, dickite, hydrated halloysite, nacrite and others.

For this family of minerals, the lattice charges are balanced internally and the charge on the mineral is due only to terminal O ions on the lattice edges. Members of this group exhibit only slight hydration and adsorptive properties. The cation exchange capacity of the Kaolin group is low.

There are two subgroups to the hydrated mica family of minerals. They are illite and chlorite. The cation exchange capacity of the hydrated mica minerals is lower than that of the montmorillonite group and greater than that of the kaolin group.

The Montmorillonite group of clay minerals is characterized by its expanding lattice. The crystal lattice expands and contracts with the amount of water that is present. Water and cations are absorbed not only on the outer surfaces, but also on the internal surfaces between the lattices. This type of mineral has a large internal surface and a high

cation exchange capacity. Members of the montmorillonite group are montmorillonite, saponite, beidellite and nontronite.

The Fibrous clay group and the mixed layer group have not been studied extensively.

3.4 Shape and Surface Properties of Clay Particles

It has been established that clay particles are non-spherical in shape (Baver 1956). As a result of ultra-microscope investigations, double refraction phenomena, observations of the characteristic layering of clay particles during deposition and the fact that the crystal lattice of clays is formed by sheets of alumina and silica, it was proposed that clay particles were plate shaped or disc-shaped. With the advent of the electron microscope, it was found that both plate shaped and rod shaped clay particles exist.

Thomson (1960) gives the shape of various clay minerals as determined by electron microscope as follows:

- (1) Montmorillonite structure ranges from amorphous appearing material to extremely thin plates.
- (2) Beidellite particles are well defined and plate-like.
- (3) Kaolinite particles are hexagonal plate shaped with sharp, well defined edges.
- (4) Halloysite particles, similar to kaolite in crystal structure, are well defined and rod-shaped.

The shape of the clay particles is important from the physical point of view. Plate-shaped particles have a high specific surface (ratio of sur-

face area to volume of particle). A given volume of clay has a much greater total surface area than the same volume of sand or silt. As adsorption is a surface phenomenon, it can be seen that the cation exchange capacity of clays will be tremendously greater than that of sands or silts.

It is obvious that disc-shape particles can be arranged in more intimate contact with one another than can spherical particles. When the orientation is favorable, disc-shaped particles provide large contact surfaces and cohesion will be great. Also, laminar particles can slide over one another under a load, whereas spherical particles will allow deformation only if the grains roll apart or actual shearing of the particles occurs.

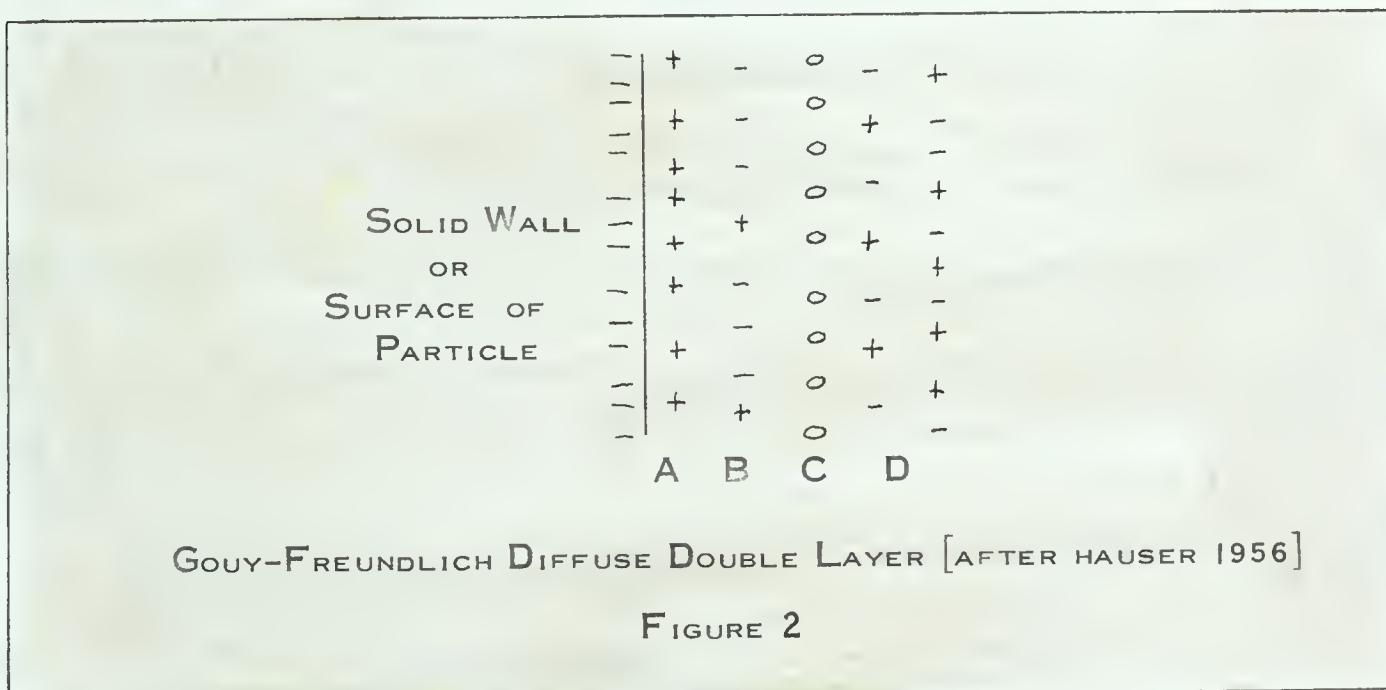
3.5 Adsorption and Water Films

Adsorption may be defined as a change in concentration occurring at the interface or phase boundary between solids and liquids, liquids and gases and solids and gases. (Mielenz 1955) (To date there has been very little research on the adsorption of gases by clay particles.) Adsorption may be the result of electrical unbalance (Coulombic forces) or gravitational forces (Van der Waal's forces).

The electrical unbalance causing adsorption arises, in part, through substitution of ions of differing valency in the clay crystal, at broken electrostatic bonds of the crystal, and at areas of polarization. Adsorption may take place at the edges and sides of the clay minerals and between the crystal sheets as in such minerals as montmorillonite (Mielenz 1955). The electrical unbalance in clay minerals usually results in a de-

ficiency of positive charges in the crystal lattice and hence the mineral particles assume an overall negative charge. It is known that a colloidal particle will travel in suspension toward a positive or negative pole, depending on whether the charge on the particle is negative or positive.

A clay particle in suspension will travel to a positive pole. This clay particle is not dry, but is surrounded by a hull or layer of adsorbed water which is formed on the particle due to a double layer phenomenon. This double layer effect was first partially explained by H. von Helmholtz in 1897 and since then the theory has been amended by various workers (Hauser 1956). The Gouy - Freundlich adaption of Helmholtz' s theory is shown schematically in figure 2.



The negative charges on the clay particles attract water molecules and ions from the surrounding liquid phase. The molecules of water and ions which are in close proximity to the surface of the particle are held firmly on the soil particle (figure 2, A). Outward from the soil

particle the orientation and attraction of the water and cations diminishes and a point is reached, (figure 2, C) beyond which the charge on the clay particle exhibits no influence on the water or cations (i.e. at D, figure 2).

The diffuse double layer consists of the water molecules and ions either belonging to or firmly adsorbed on the surface of the particle and of the counter ions and water molecules which surround it at a distance. This distance depends upon the magnitude of the charge on the particle and the hydration of the cations. The clay particle plus its diffuse double layer is called the clay micelle.

Thus it may be seen that the clay micelle consists of two parts the inner part consisting of the clay particle with its overall negative charge and the outer shell of adsorbed water and hydrated cations. The thickness of the adsorbed water hull is difficult to determine as there is a gradual transition from rigidly held water near the surface of the particle to the free pore water of the system. Coates (1954) states that water films may be as thick as 10^{-4} mm.

Coates (1954) outlines a hypothesis explaining the adsorption of water on montmorillonite. Firstly, the adsorbed cation is surrounded with water molecules, the number of which varies for each cation. The figures given are: 6 adsorbed molecules on each Ca^{++} and Mg^{++} ion, 3 for Li^+ , but none for Na^+ , K^+ or H^+ . Secondly, the first molecular layer of water is formed around the soil particle. The third step

is the formation of a second molecular layer of water around the soil particle. Any extra water is believed to be held by capillary action only. It is felt that the cations take up their molecular water when the relative humidity is 10% or less. The completion of the first layer of adsorbed water around the soil particle occurs at relative humidities greater than 40 %.

Many theories explaining the mechanism of the physical properties of soils such as plasticity, shrinkage and swelling, permeability and consolidation have been developed and most of them are based on the action of the adsorbed water films. The properties of these adsorbed films are affected by the nature and quantity of adsorbed ions and will be discussed in Chapter 5.

CHAPTER 4

CATION EXCHANGE4.1 Definition of Cation Exchange

The reversible process by which one cation goes from solution into insoluble form and another comes into solution to take its place is known as cation exchange. Anion exchange also occurs but apparently to a much lesser extent. Little work has been conducted on anion exchange due to the complicated laboratory procedures involved (Grim 1952). However, it is known that anion exchange is most important in the kaolinite minerals where anions replace the OH^- groups.

The cation exchange capacity * of a soil is the total amount of cations that the soil can adsorb under a given set of conditions. It is not a constant but varies with the pH of the soil.

Exchange capacity is usually expressed as milliequivalents of cation per 100 grams of oven dry soil. An equivalent weight is the amount of reagent which contains or reacts with one gram atomic weight of replaceable hydrogen or with one gram molecule weight of hydroxyl. A milliequivalent is $1/1000$ of an equivalent weight. For the purposes of this thesis, a milliequivalent may be defined as one milligram of hydrogen (H^+), or the amount of any other cation that will displace it.

If the cation exchange capacity is known for a soil, the amount of any particular cation that it can adsorb may be determined from the following relationship:

* Normally referred to merely as "exchange capacity".

Grams adsorbed per 100 gram of soil =

$$\text{m.e. per 100 gm.} \times \frac{\text{atomic wt. of cation}}{\text{valence of cation} \times 1000}$$

For example, if a soil has a cation exchange capacity of 40 me/100g., it can adsorb:

$$40 \times \frac{1.008}{1 \times 1000} = 0.0404 \text{ gms of H}^+ ;$$

or,

$$40 \times \frac{40.08}{2 \times 1000} = 0.8016 \text{ gms of Ca}^{++} ;$$

or,

$$40 \times \frac{17.03}{1 \times 1000} = 0.6812 \text{ gms of NH}_4^+ ;$$

per hundred gram of oven dry soil.

4.2 Causes or Sources of Cation Exchange

The two sources of cation exchange that seem to be most significant are:

- (1) Isomorphous substitution within the crystal lattice of such minerals as montmorillonite and illite.
- (2) Unsatisfied valences at the terminal edges of the lattice layers of such minerals as kaolinite and halloysite.

Isomorphous substitution is the replacement of one ion for another of different valency within the crystal lattice. The aluminum ion in montmorillonite can be replaced by iron and magnesium ions. Some silica in montmorillonite can be replaced by aluminum (Coates 1953). When a trivalent ion is replaced by a bi-valent ion within the crystal, the balance of valences is upset, and a resultant negative charge is imparted to the mineral.

According to Grim (1939), the substitution of iron and magnesium for aluminum results in a charge which is not strong enough to hold the crystal sheets together and water may enter between the lattice causing expansion. The magnitude of this charge is great enough, however, to hold exchangeable cations. The expansion of montmorillonite may be considered to be due to the hydration of the exchangeable cations between the sheets, resulting in a pushing apart of the crystal lattices. The unbalancing of valences also happens in montmorillonite by the aluminum and iron ions being leached out of the lattice by an acid or salt solution.

Kelly (1948) points out that unbalanced charges on the edges of montmorillonite play a small part in the total cation exchange capacity. However, as the total area of these terminal edges is small compared to that of the flat edges, the contribution of these terminal edges to the total cation exchange capacity of the mineral may be disregarded.

Broken bonds of the sheet-like lattices result in electrostatic forces at the edges of the crystals. Here both cations and anions can be adsorbed as there are both positive and negative charges on the crystals. For kaolinite and halloysite this is thought to be the only source of cation exchange capacity (Grim 1939).

4.3 Range of Cation Exchange Capacity for Various Minerals

All clay minerals possess a cation exchange capacity. However, the capacity varies greatly due to different particle size distribution, differences in crystal structure and differing atomic substitution. As only limited isomorphous substitution occurs in kaolinites, and because

kaolinite minerals are comparatively coarse, the cation exchange capacity of this mineral is low. As previously stated, the charges on this mineral are caused by broken electrostatic bonds and adsorption occurs solely on the external surface of the mineral (Mielenz 1955).

Isomorphous substitution and the very fine size of montmorillonite particles results in a much higher exchange capacity for this clay.

Illite has an intermediate cation exchange capacity.

Ranges of cation exchange capacity for some of the common clay minerals, as recorded by Mielenz (1955), are shown below.

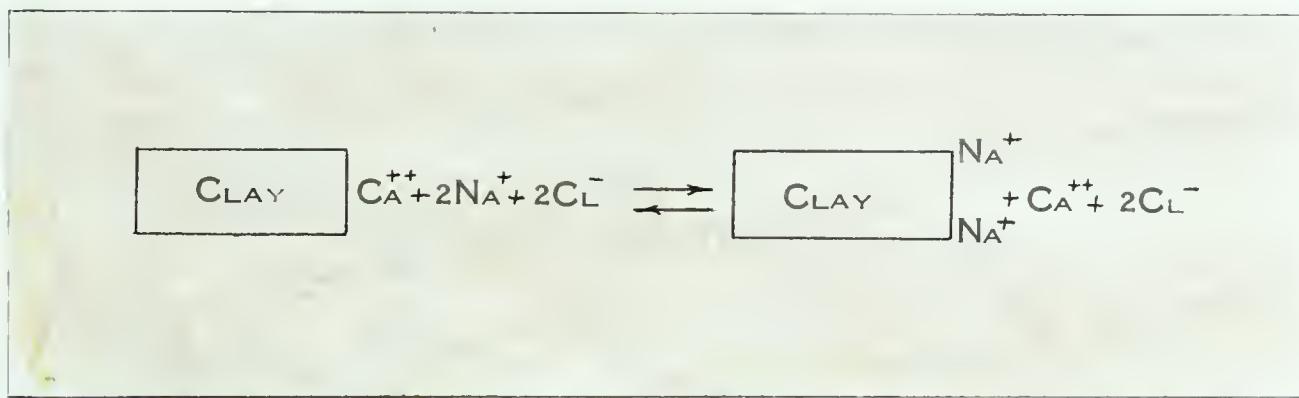
MINERAL	CATION EXCHANGE CAPACITY (m.e. per 100 g.)	
Montmorillonite	60	- 160
Illite	20	- 40
Kaolinite	2	- 15
Halloysite	6	- 70
Attapulgite	25	- 30
Vermiculite	65	- 146

4.4 The Cation Exchange Process

Cation exchange is not an essential property of material in the colloidal state, but rather is associated with certain kinds of surfaces. Substances such as finely divided gold, sulphur, platinum and certain sulphides are examples of colloidal substances but they exhibit only a very slight cation exchange capacity as compared to clay minerals (Kelly 1948). Clay is chemically active and reacts with salts as if it were a salt itself. Shawarbi (1952) states that colloidal clay may be regarded as a very com-

plex salt, the acid part being a complex alumino-silicic acid and the basic part being aluminum, calcium, magnesium, potassium, sodium and hydrogen.

The cation exchange reaction may be depicted as is shown in the following diagrammatic formula after Shawarbi (1952).



In solution* the exchange process is so quick as to appear instantaneous.

Consider a homionic calcium clay, (a clay with all the exchange positions occupied by Ca^{++}), in distilled water. Initially, little, if any cation exchange will occur. If sodium chloride is added to the water, sodium ions exchange places with the calcium ions yielding a sodium clay. The reaction is instantaneous in solution and does not cease at this point.

Sodium ions on the soil are again replaced by Ca^{++} and so on. This reaction attains a dynamic equilibrium at which a definite amount of each cation will be adsorbed on the clay. The speeds of the forward and reverse reaction are seldom the same and a mixed system results which does not contain equal proportions of adsorbed bases.

- * The term solution, is used to describe a low soil:solution ratio of say, 1:50.

Hence, if it was desired to replace the original cation by one in solution, it would be necessary to continually apply the solution, gradually washing off the adsorbed ion and replacing it with the cation in solution. In this way, the concentration of the original cation is reduced and also the effectiveness of the reverse reaction until the latter ceases. Theoretically, for the example given in the diagram, if the original clay with Ca^{++} cations adsorbed was washed continually with a solution of Na Cl , a homionic clay with only adsorbed Na^+ would result.

According to Jenny's theory (Baver 1953), the adsorbed cation is not immobile but oscillates. The exchange reaction may be visualized as resulting from ions in solution slipping in behind the oscillating adsorbed ion and displacing it. Ions which are weakly hydrated, (have the thinnest water hull), have a small amplitude of oscillation. Those which exhibit a great amount of hydration have a large amplitude of oscillation. For these ions, the water hull prevents close contact with the soil particle and the electrostatic attraction between the ion and the particle is less than that for weakly hydrated ions.

4.5 Factors Affecting Cation Exchange Reaction

In solution, the rate of cation exchange is rapid and usually only a few minutes are required for equilibrium to be reached. The speed of the reaction may be increased by shaking or mixing the soil solution with high speed electrical mixers. It has been found that 50 grams of soil in 500 cc. of 1N NH_4Cl will achieve equilibrium by shaking for only three

minutes (Kelly 1948). For complete exchange to be attained, diffusion of ions to the inner surfaces between the sheets of the clay minerals must occur. Thus, it is to be expected that a longer period of time will be required for exchange to occur in montmorillonites (which adsorb most of the cations between the sheets) than in kaolinites.

Thomson (1960) found that if the soil-solution ratio is small, say, 1:2, that several days are required for the cation exchange reaction to reach equilibrium.

Kelly (1948) cites Way, who pointed out that cation exchange is influenced by the ratio of the weight of soil to the volume of solution used. The lower the ratio of soil to solution, the higher the cation exchange capacity is for a given soil. This holds true to a ratio of 1:100, below which further increase in cation exchange is small.

It has also been found that a temperature increase will speed up the exchange reaction. However, it is not recommended to heat above, say 20°C as the solubility of certain constituents in the soil may increase with temperature, and the total exchange capacity of the soil may be altered.

Kelly (1948) points out that the concentration of the solution has a marked effect on the exchange reaction. With cation pairs of similar replacing power and of the same valence, such as K^+ and NH_4^+ , or Ca^{++} and Ba^{++} , dilution has little or no effect on exchange. With cations of different replacing power and different valence such as Na^+ vs Ca^{++} ,

dilution produces a substantial decrease in the power of the monovalent Na^+ to replace exchangeable Ca^{++} .

Ion exchange equilibrium varies a great deal with the nature of the exchange material. Different types of clay minerals have differing exchange capacities depending upon the magnitude of the surface charge density. The non-uniformity of the mineral surface and variations in the charge density over the surface results in varying concentrations of adsorbed cations over the particle surface.

The geometric fit of ions into the mineral structure also effects cation exchange. If an ion fits well into an exchange spot, it will become more firmly adsorbed than ions not having this size.

Clogging of exchange positions reduce the cation exchange capacity of a soil. This may occur if an ion is too big to enter between the basal or interior surfaces of the minerals. Clogging may also occur by adsorption of large, flat organic ions which cover more than one exchange spot.

4.6 Relative Replacing Power of Cations

Many experiments have shown that there is no single universal order of the replacing power of cations (Wiklander 1955). However, it has been found that the relative replacing power for soils often increases with an increase in valency of the cations. A monovalent ion is usually more easily displaced by a bivalent ion, etc.

From the previous discussion on the factors affecting the exchange reaction, it may be concluded that the relative replacing power depends upon:

1. The exchange material and its exchange capacity
2. The valence of the ions (adsorption is stronger for multi-valent ions than for monovalent ions)
3. The size of the hydrated ions (weakly hydrated ions are most strongly adsorbed)
4. The concentration of solution

CHAPTER 5

SOME PHYSICAL PROPERTIES OF SOIL AND
THE EFFECTS OF CATION EXCHANGE5.1 Flocculation and Dispersion

Thomson (1960), cites Lambe, who divides the cations into two categories according to their effect on the structure of soil -- flocculating cations which cause a linking together of soil particles into an agglomerated form and dispersing cations which cause the soil particles to become separated. A well dispersed clay is more impermeable, elastic, compressible and exhibits higher dry strength than does an agglomerated form occupying the same volume. The state of dispersion affects the amount of water adsorbed by a clay mass and consequently influences many of its properties. Johnson (1947) states that it is possible that one of the major applications of chemistry to soil mechanics may be in adjusting clay masses to be more or less flocculated.

It is known that an homionic sodium clay is highly dispersed, whereas an homionic calcium clay has a granular or flocculated structure. Investigations by many workers show that there is a close relationship between the degree of dispersion of a colloidal system and the zeta potential (Baver 1956). The effect of the adsorbed cation on the zeta potential can be explained as follows by using a calcium-saturated clay and a sodium saturated clay for examples.

The calcium ion has a relatively small hydrated radius and is divalent and thus is held tightly and closely to the surface of the clay par-

ticles. The proximity of the calcium ion to the clay surface causes a relatively low zeta-potential and tends to neutralize the charge on the clay particle. This neutralization reduces the repulsive force acting between clay particles of like charge and the clay particles tend to agglomerate or flocculate. Baver (1956) states that it is necessary only to lower the zeta-potential to a certain value, the critical potential, in order to produce flocculation.

The sodium ion, on the other hand, has a relatively large water hull (is highly hydrated), and when is adsorbed on a clay particle is held much more loosely and at a greater distance from the surface than is the calcium cation. This causes a large zeta-potential and a repulsive force between the clay particles. This repulsive force maintains the Na - clay in a state of dispersion.

Coates (1954) describes an investigation in which homionic montmorillonite clays were treated with salts to vary the magnitude of the zeta potential. Those samples which were adjusted to have a zeta-potential of -40 millivolts (dispersed), had, at a load of 1 ton per square foot, a void ratio three times greater than those with a zeta-potential of -20 millivolts (flocculated).

Flocculation may be produced in different ways. It is known that it may be promoted by increasing the concentration in solution of the adsorbed cation.

Also, by exchanging the adsorbed cation for one of higher valence, the ease of flocculation is increased. This is to be expected because, in

general, the thickness of the adsorbed water films decreases with an increase in valence of the cation.

5.2 Plasticity and the Atterberg Limits

The consistency of a clay varies greatly so that it exhibits plasticity over only a portion of the moisture content range. In 1911, Atterberg defined the limits of the plastic range.* Plasticity may be defined as the ability of a soil to undergo rapid changes of shape without rupture or to be deformed by shear without cracking or crumbling and without noticeable volume change.

Many theories have been devised to explain the causes of plasticity and to account for the conditions that occur in a soil when it is at the liquid and plastic limits. One of these theories, presented by Grim (1950), seems to adequately explain the plastic behaviour of clays. According to this theory, water is adsorbed on the basal surfaces of the plate-shaped clay minerals. The water molecules have a definite orientation in the first layers adsorbed. These oriented water molecules do not exhibit fluid properties but are rigid like ice. The degree of orientation of the

* The liquid limit (W_L) is the moisture content of a soil when it is at the boundary between the liquid and plastic states.

* The plastic limit (W_P) is the moisture content of a soil when it is at the boundary between the plastic and semi-solid states.

* The plastic index (IP) is the numerical difference between W_L and W_P .

water molecules decreases outward from the clay and at some distance from the clay mineral surface, the water molecules are not oriented; that is they are fluid. At low moisture contents the rigid water serves as a bond to hold the clay particles together. The soil mass becomes plastic when there is enough water to supply all the particles with oriented or rigid water films, plus a small quantity of water which has little or no orientation to act as a lubricant between flakes. At this point, the plastic limit is reached. Large amounts of additional water provide much fluid water and give the system the properties of a fluid. The moisture content at which these fluid properties become apparent is the liquid limit of the soil.

Cation exchange is assumed to affect the consistency limits by changing the perfection of orientation of the water molecules, the thickness of good orientation, and the abruptness of the transition from oriented to non-oriented water.

5.3 Factors Affecting the Atterberg Limits

Three major factors may be considered as significant in accounting for variations in the Atterberg Limits:

- 1) the specific surface of the soil;
- 2) the nature of the clay mineral;
- 3) the nature of the adsorbed cations.

Plasticity is a function of the finer soil fractions, in particular the clay-size particles. For a given soil, an increase in clay content will cause the liquid and plastic limits to be higher on the moisture scale and

an increase in the plasticity index will occur. The increase in the percentage of clay causes the specific surface of the soil to be greater and more water is required to satisfy the surface forces of the clay.

The plastic properties of soil materials is also largely dependant on the type of clay minerals that compose them. Grim (1950) lists Atterberg Limit values for pure clay-mineral soil samples and shows that the kaolinite and illite exhibit plasticity properties (W_L , W_P and PI) that are roughly the same. The plastic limit for montmorillonite can be over three times that for kaolinite or illite, while the liquid limit may be as much as six times as great as that of kaolinite or illite. The high plastic properties of montmorillonite are due to its property of breaking down into exceedingly small flake-shaped units with a consequent tremendous surface area with particular ability to adsorb water.

The nature of the exchangeable cation has a considerable influence upon soil plasticity (Baver 1956). It is probable that the effects of the adsorbed cation on the Atterberg Limits of a soil is due to its effects on both water adsorption and interparticle attraction. The sodium cation, for instance, has a thick water hull and when adsorbed on a soil, causes a dispersed structure due to the high zeta-potential induced. The calcium cation, on the other hand, produces low zeta-potentials and flocculation of soil particles. Its hydrated water hull is thin. In order to obtain plastic characteristics, the soil must contain an excess of water above that required to satisfy the sorptive capacity of the particles for water.

The amount of water adsorbed depends upon the hydrateability of the cations adsorbed on the soil and hence it is to be expected that an Na^+ - soil would exhibit higher Atterberg Limits than would a Ca^{++} - soil. According to Baver (1956), K^+ - saturated soils require less water to produce these plasticity effects than do Na^+ - saturated soils. The Ca^{++} - and Mg^{++} - soils require a certain amount of water to fill the pores of the flocculant structure and therefore a larger quantity of water is necessary to produce plasticity than in the case of the K^+ - saturated soils.

5.4 Swelling and Shrinkage

Thomson (1960) cites Ladd, who states that the swelling of clays upon reduction of the effective stress on a clay sample is due to an osmotic repulsive pressure. If an aqueous solution and pure water are separated by a semi-permeable membrane, it is found that water moves through the membrane to dilute the solution. This process is known as "osmosis". To explain the swelling of clays, it is proposed that the electric double layer around the soil particle acts as a semi-permeable membrane which allows water to enter the clay micelle but will not permit cations to enter except through replacement of other cations in the micelle. In most clays, the concentration of cations is greater within the double layer than in the pore fluid. This difference in concentration results in water entering the clay micelle resulting in a repulsive pressure between adjacent particles and swelling of the clay. It was found that this repulsive pressure is proportional to the difference in the ion concentration in the clay micelle and in the free pore water.

It has been proposed by Thomson (1960) that the swelling of saturated clays can be reduced in two ways:

- (1) By the replacement of low valency exchangeable cations for cations of higher valency, i.e. reducing the concentration of cations in the double layer.
- (2) By leaching the clays with salt solutions of sufficient strength to increase the concentration of cations in the free pore fluid.

Clays of the expanding lattice type such as montmorillonite, in the non-saturated state, undergo swelling which is caused by the hydration of cations between the mineral sheets. A great amount of swelling is exhibited by bentonite, (sodium montmorillonite) upon addition of water, due to the great hydrateability of the sodium cation.

The shrinkage of clays is caused by (1) decreasing the amount of water in the interlayers of expanding lattice type minerals and (2) increasing compressive stresses originating in capillary forces as water evaporates. Shrinkage is greater for montmorillonite type clays than for illite or kaolinite because of the greater fineness of the particles, thicker adsorbed water films and interstitial water (Thomson 1960). For any one type of clay, it follows that dispersing cations should produce greater shrinkage upon drying than flocculating cations. The latter produce a granular structure with greater pore sizes and hence, capillary forces will be less than in dispersed clays. Also, dispersing cations have relatively thick hulls of adsorbed water as compared to flocculating cations, and with drying, soils containing the former should exhibit greater shrinkage.

It has been proven experimentally that sodium and potassium clays exhibit greater shrinkage and swelling characteristics than do calcium and magnesium clays (Winterkorn 1941).

5.5 Consolidation and Permeability

Terzaghi's consolidation theory describes the process of consolidation as a reduction in void ratio of a saturated soil sample through the squeezing out of water under an applied load. This conception is valid for primary consolidation only. Secondary consolidation, which occurs to more or less some extent in all clays, is generally attributed to a gradual structural readjustment under the applied load.

Generally, it has been found that the void ratio under a given load for a dispersed soil is greater than that for a flocculated soil (see section 5.2). Thus, it is to be expected, that a dispersed soil such as a Na^+ - clay should undergo greater consolidation than a flocculated soil such as a Ca^{++} - clay under a given pressure. In a dispersed soil, the clay particles are arranged in a "stack of plates" fashion, and are held apart by the repulsive forces acting between clay particles and by the thick adsorbed water layers surrounding the cations and the soil particles (Seed 1960). In a soil containing montmorillonite, the dispersing cations tend to cause the clay mineral sheets to become separated by hydration of the cations between the sheets. Thus, a dispersed soil mass, consists of a uniform distribution of clay particles, surrounded by viscous water films of relatively great thickness and the space occupied by free or fluid pore water is small. Movement of water through the soil must occur

through the space occupied by the free pore water as the viscous adsorbed water on the cations and soil particles offers resistance to flow. A flocculated soil, on the other hand, has a random structure in which the clay particles are arranged in a "card house" structure which is maintained by the attractive force acting between the clay particles. The thickness of the viscous or adsorbed water films around the flocculating cations and soil particles are relatively thin and hence the space between the agglomerated soil particles which is occupied by free water is large as compared to that of the dispersed soil. Thus, the permeability of a flocculated soil is usually much greater than that of a dispersed soil mass under a given load.

Due to the lower permeability of a dispersed soil, the rate of consolidation is generally much slower than that of a flocculated soil.

An apparent exception to the above generalization is the K^+ - cation which appears to produce a flocculant structure instead of the expected dispersed structure when it is adsorbed on a clay. Baver (1956) holds, however, that the K^+ - cation does produce a dispersed soil and that the relatively low plasticity characteristics that are exhibited by potassium clays are due to the low hydration of the K^+ - cation and hence less water is required to produce plasticity than for other dispersed soils such as the Na^+ - clay (see section 5.3). The permeability of K^+ - clays has been found by Cornell University to be lower than that of Ca^{++} or Mg^{++} clays (see plate 3) and this would further indicate a dispersed structure.

CHAPTER 6

TESTING PROGRAMME

6.1 Preparation of Soil for Testing

The soil chosen for this research programme was a highly plastic, dark brown clay* from the Edmonton, Alberta region. It was removed from a relatively fresh highway cut from below the zone of weathering and transported to the laboratory where approximately 5,000 grams was air dried and ground down to pass the No. 40 sieve. Through a quarter-ing procedure, the soil was split into 200 gram portions which were placed in quart sealers. It was felt that the samples prepared in this way were homogenous and representative of the entire specimen.

In all, twenty-five sealers each containing 200 grams of soil were prepared:-- five samples were unaltered and tested as "natural soil"

ten samples were transformed into homionic soils by methods outlined in the following pages

the last ten samples were set aside for the final phase of the programme which was the determination of the effects of the Na^+ cation on a homionic Ca^{++} clay.

The quart sealers were capped and were stored in the air dry state until needed for testing.

6.2 Testing of Natural Soil

The one thousand grams of air dried natural soil was subjected to the following tests: -- grain size analyses

-- specific gravity

$$* W_1 = 76.1\%; W_p = 28.9\%; I_p = 47.2\%$$

- Atterberg limits
- cation exchange capacity
- determination of exchangeable cations
- carbonate content through reaction with hydrochloric acid
- consolidation tests

The grain size analyses, the specific gravity tests and the Atterberg limit tests were performed in accordance with ASTM Designations: D422-54T, D854-52, D427-39, D423-54T, and D424-54T, respectively. The data sheets for these tests are included in appendix A.

The cation exchange capacity for the natural soil was determined by the Alberta Soil Survey procedure as outlined by Thomson (1960).

The determination of the type and quantity of the adsorbed cations on the natural soil was performed by means of the Alberta Soil Survey method with the use of a model DU Beckman Flame Photometer (see Thomson (1960) for a detailed description of procedures).

An indication of the presence of carbonates in the natural soil was obtained through the addition of HCl to the clay. Extreme effervescence indicated a relatively high percentage of free carbonates.

The results of the classification tests for the natural soil are shown in table 1. The mineralogical composition shown is only approximate, and is based on previous tests performed on soil samples from the same general area.

Consolidation tests on the natural soil were performed as follows: approximately 100 grams of the air dried soil was mixed with distilled

SUMMARY OF CLASSIFICATION TESTSNATURAL SOIL

1.	SPECIFIC GRAVITY	2.76
2.	GRAIN SIZE DISTRIBUTION	
	% Sand	7%
	% Silt	48%
	% Clay (a) > 0.2 micron	29%
	(b) < 0.2 micron	16%
3.	ATTERBERG LIMITS	
	Liquid Limit	76.1%
	Plastic Limit	28.9%
	Plasticity Index	47.2%
	Shrinkage Limit	9.7%
4.	TOTAL EXCHANGE CAPACITY (me. / 100g)	25.1
5.	EXCHANGEABLE CATIONS	
	Sodium (Na)	4.0%
	Potassium (K)	3.2%
	Calcium (Ca)	50.0%
	Magnesium (Mg)	42.8%
6.	PROBABLE MINERALOGICAL COMPOSITION	
	Montmorillonite	20% - 40%
	Illite	20% - 40%
	Chlorite	10% - 25%
	Kaolinite	10% - 25%
7.	CARBONATE CONTENT	HIGH
8.	CASAGRANDE CLASSIFICATION	CH

water until a moisture content approximately equal to the liquid limit was reached. The sample was then covered and allowed to stand in the moist room for a period of forty-eight hours to permit complete dispersion of moisture throughout the soil. A standard consolidation ring one inch in thickness and 2.60 inches inside diameter was placed on a glass plate. A circular disc of filter paper, cut to the exact diameter of the ring, was placed inside the ring flush with the glass plate. The ring was then filled with soil in five lifts. Tamping and kneading with a spatula was employed to remove as much entrapped air as possible. The soil was scraped flush with the top of the ring and a second filter paper placed on the top of the specimen. The soil, ring and filter paper was then weighed and placed in the consolidation dish on the pan of the loading machine. A loading head with attached porous bronze plate was placed on the sample and the extensometer dial for measuring deflection was attached. The loading yoke was brought into contact with the loading head and a zero-load reading of the extensometer dial was recorded. An initial load of approximately $.07 \text{ kg/cm}^2$ was applied to the sample and deflection readings were taken at 6 seconds, 30 seconds, 1 minute, 2 minutes, etc., doubling the time interval between readings. Increments of load ranging from 0.07 to 14.9 kg/cm^2 were employed and the sample was then unloaded to the original 0.07 kg/cm^2 in two steps. Each load increment was left on the sample until primary consolidation was completed and a portion of the secondary consolidation curve had been established. It was found that the use of filter paper on the ends of the sample successfully prevented

squeezing out of the soil between the filter plate and the ring. At the conclusion of the tests, the specimens were weighed and then oven dried to determine moisture contents and void ratios.

The coefficient of permeability of the natural soil was computed from the consolidation test data for the 0.60 to 1.18 kg/cm² load increment. Data sheets for consolidation tests are enclosed in Appendix A. Data obtained from the consolidation test on the natural soil is shown in table 4.

6.3 Preparation of Homionic Modifications

6.3.1 General

Homionic soil can be produced by leaching the soil with a reagent containing the desired cation until all the original cations on the soil have been replaced (see section 4.4). Placing the soil in a given amount of reagent, mixing and allowing it to stand for a given period of time will not result in complete exchange (Thomson 1960). This procedure results in a mixed system with two or more types of cations adsorbed on the soil and also present in the pore water.

Thomson (1960) recommended a procedure for producing homionic soils which involved washing the soil with a continual supply of solution containing the desired cation. He felt that a satisfactory method would be to force the solution through the soil under pressure using a filtering device to prevent removal of the finer soil fraction. The initial attempts to produce homionic soils were based on this recommendation.

6.3.2 Initial Attempts

As relatively large quantities of homionic soil were required for this investigation, it was felt that filtering procedures such as forcing the solution through soil contained in Buckner funnels would be too time consuming. It was found that only small quantities of soil could be treated in this way and that large quantities of leaching solution were required. To produce the quantity of homionic soil required for the investigation by using this filtering method, many weeks of laborious work would be required.

To speed up the treatment process, an apparatus was constructed with which it was hoped that much larger soil samples could be transformed into the homionic state. The apparatus consisted of a vertical leaching tube, made of plastic, approximately 3.5 inches in diameter and 3.5 feet in length. On the upper and lower ends, removable porous bronze plates were attached. A five litre bottle for the leaching solution was connected to a vertical rod in such a way that it could be moved up and down. This bottle was connected to the bottom of the leaching tube with one-quarter inch diameter plastic tubing. Inside the leaching tube, a nozzle attachment was fitted immediately above the lower filter plate, and the plastic tubing from the five litre bottle was attached to the nozzles. Approximately 100 grams of soil was placed in the bottom of the tube, the five litre bottle was filled with a solution containing the desired cation and this solution was allowed to flow into the leaching tube through the nozzles. By moving the bottle up or down, the flow of sol-

ution was regulated until the majority of soil particles were maintained in suspension. The solution, upon reaching the top of the tube, passed through the fine filter plates and was discarded. It was planned that through trial and error, the amount of leaching solution required to produce homionic modifications would be determined. Removal of excess cations from the solution surrounding the soil particles was to be achieved by repeating the leaching procedure using distilled water.

Unfortunately, it was found that the finer soil particles passed through the upper filter in suspension and were lost. Different types of filters were tried, including the finest filter paper available, but none succeeded in preventing the washing out of the fine clay particles. It was concluded, that this procedure could be used successfully, if semi-permeable membranes and very high leaching pressures were used. Unfortunately, time and lack of equipment prevented further development of this apparatus.

6.3.3 Method Used

A total of 1000 grams of soil was used in this phase of the experiment. One quart sealer containing 200 grams of soil was used for pilot tests to determine if the procedure would, in fact, result in homionic clays. The soil in the remaining four quart sealers was converted into 200 gram portions of homionic sodium, potassium, calcium and magnesium clay by the method outlined below.

Initial tests on the natural soil indicated a high percentage of carbonates. Carbonates in a soil tend to lower the total exchange cap-

acity, as the large carbonate crystals occupy space in the soil mass which would otherwise be occupied by clay minerals. Also, if carbonates are present, homionic soils cannot be produced as the addition of any water to the soil will cause these carbonates to dissolve, thus releasing extraneous cations in the pore water. As a result, two or more cations may become adsorbed on the soil. To remove these carbonates, each sealer containing 200 grams of soil was subjected to three washes with hydrochloric acid. Five hundred cc. of 0.1N HCl was added to each sealer, mixed thoroughly with an electric mixer and the soil was then allowed to settle to the bottom of the sealer over a period of from two to three days. The supernatant liquid was then syphoned from the sealer and the above procedure was repeated twice. In this way, all carbonates were removed from the soil and a clay having only adsorbed hydrogen cations was produced. After the final acid rinse, approximately 100 cc. of acid remained in each sealer as it was not possible to remove all the fluid from the soil by syphoning. The sealers were then capped and left in the moist room until needed.

To replace the hydrogen adsorbed on the soil with the desired cation, a second washing procedure was used involving 1N Acetate solutions. The acetates used were: sodium acetate, magnesium acetate, potassium acetate and calcium acetate. Each 200 grams of soil was washed with three, 500 cc. portions of the acetate containing the desired cation. After each addition of acetate, the mixture was thoroughly stirred, the clay particles allowed to settle out and the supernatant liquid was

drained off. It was found that three washes were sufficient to replace all the hydrogen cations and to remove all HCl from the solution. A period of ten days was required to treat the four - two hundred gram samples.

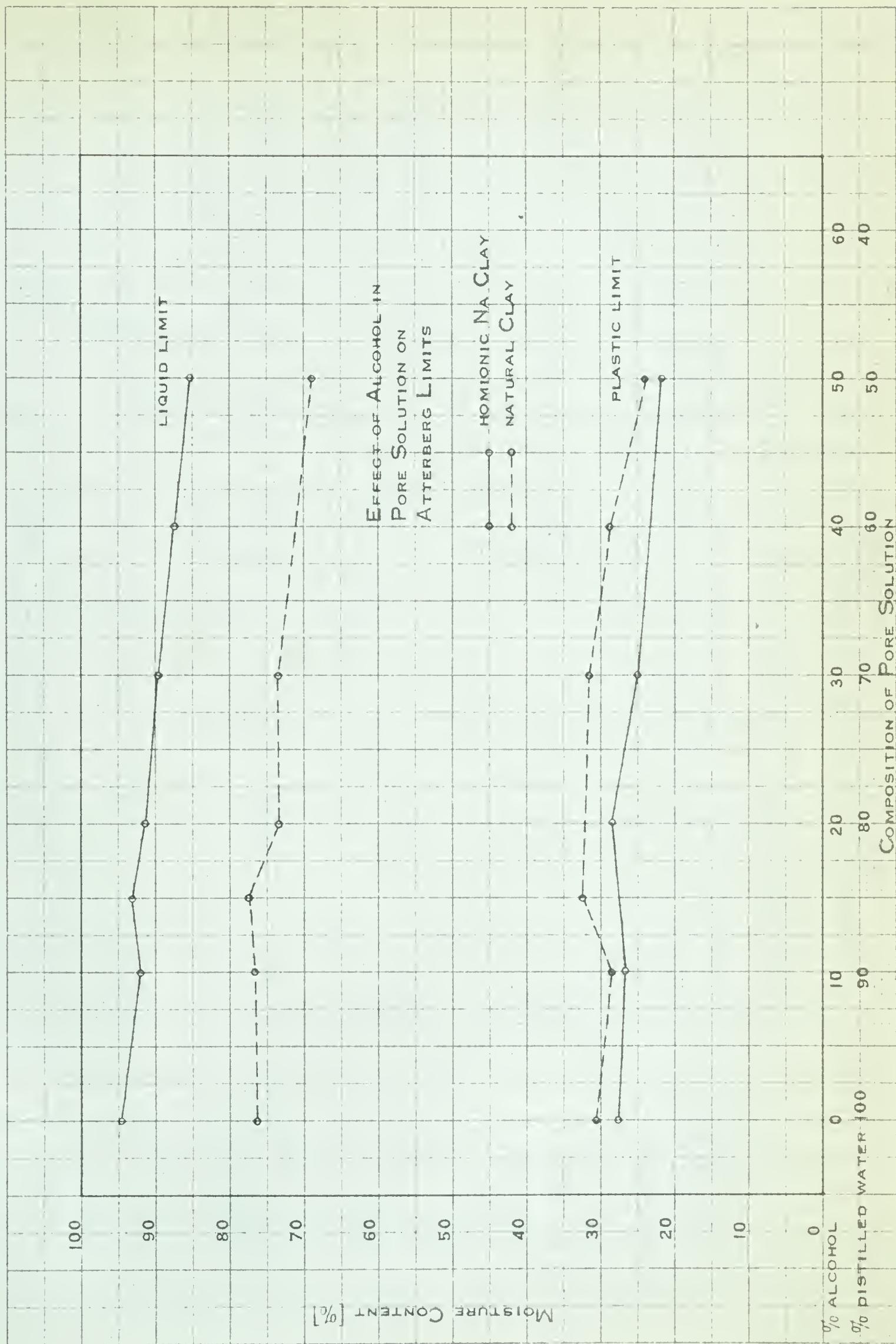
The final step in the production of homionic soils was to remove the excess cations remaining in the soil solution from the acetate washes. This was accomplished by using methyl alcohol as the washing solution. Distilled water was not used as it was found that the clays remained in suspension when mixed with water and would not settle out. However, with the use of alcohol, the clay particles flocculated in suspension and settled out readily. To speed up the settling process, a centrifuge with an eight place head was used.

The soil-acetate mixture in each sealer was transferred into sixteen 100 ml. centrifuge tubes so that each tube contained approximately 12.5 grams of soil and 30 cc. of acetate solution. The tubes were then filled with methyl alcohol and centrifuged, eight at a time, at 2000 r.p.m. It was found that the time of settling for the clay particles varied with the type of adsorbed cations. In general, Ca^{++} , Mg^{++} and K^+ -clays settled out in about ten minutes while Na^+ -clays took as long as two hours to settle. When the clay particles had been forced to the bottom of the tubes, the clear alcohol-acetate liquid was drained off, more alcohol was added to the tubes, the soil was thoroughly mixed with an electric mixer and the centrifuge procedure was repeated. It was found that four washes were sufficient to remove all acetate from the sol-

ution. After the final wash, the soil in the centrifuge tubes was saturated with alcohol at approximately the liquid limit. The soil was transferred from the centrifuge tubes into a beaker and allowed to air dry. Oven drying was not employed as this results in a change in the plasticity characteristics of the soil through a break down in the montmorillonite structure.

The hygroscopic alcohol content of the air dried soil varied from four to six percent. To investigate the effect of alcohol in the pore water on the plasticity characteristics, samples of the natural clay and of homionic sodium clay were prepared containing varying amounts of alcohol in the pore water. Liquid limit and plastic limit tests were performed on these samples and the results are shown on plate 6. From these tests, it was concluded that the small quantity of alcohol remaining in the soil after air drying would not appreciably affect the physical properties of the soil.

Five grams of the air dried soil was removed from each 200 gram sample for total exchange capacity tests and flame photometer tests to determine the type and quantity of the adsorbed cations. The results of these tests are shown in table 2. It can be seen that the removal of carbonates from the homionic soils increased the total exchange capacity of these soils over that of the natural soil. The flame photometer is accurate to about 1% and hence the results show that homionic soils had been produced. Total exchange capacity and total exchangeable cations present for each homionic soil type correspond as well as the accuracy



SOIL TYPE	TOTAL EXCHANGE CAPACITY (me. /100g)	TOTAL CATIONS PRESENT (me. /100g)						PERCENTAGE			
		Na	K	Mg	Ca	Total	Na	K	Mg	Ca	Total
Natural	25. 1*	1. 2	0. 9	12. 8	53. 7	69. 6*	1. 8	1. 3	18. 7	78. 2	100. 0
Clay											
Homionic	28. 4	31. 2	0	0	0	31. 2	100	0	0	0	100. 0
Na -Clay											
Homionic	28. 7	0	0	28. 6	0	28. 6	0	100	0	0	100. 0
Mg -Clay											
Homionic	26. 0	0	25. 3	0	0	25. 3	0	100	0	0	100. 0
K -Clay											
Homionic	27. 5	0	0	0	31. 2	31. 2	0	0	100	0	100. 0
Ca -Clay											

* Difference between total cations and total exchange capacity caused by presence of carbonates.

RESULTS OF CATION DETERMINATIONS ON
NATURAL AND HOMIONIC SOILS

of the testing procedures would permit. Thus, it may be reasonably assumed that all extraneous cations had been removed from the homionic soils. The difference between total exchange capacity and total exchangeable cations for the natural soil arises from the presence of carbonates in the soil.

6.4 Testing of Homionic Soils

6.4.1 Atterberg Limit Tests - Homionic Soils

Atterberg limit tests were performed on the homionic samples of Na^+ , Ca^{++} , Mg^{++} and K^+ -clays by the method outlined in section 6.2. It was found that approximately sixty-five grams of air dried soil was required for one complete set of limit tests on each homionic modification. One hundred grams of each air dried homionic soil was mixed with distilled water to a moisture content close to the liquid limit and was then allowed to stand forty-eight hours in the moist room before testing. The soil remaining after each set of Atterberg limit tests had been performed was again placed in the moist room and check tests were performed approximately seventy-two hours after the initial mixing to determine if the Atterberg limits for these homionic soils varied with time.

The liquid limit check tests were carried out by the one-point liquid limit method outlined by Olmstead (1958), using a tan B value of 0.121. Plastic limits tests were performed in the standard manner as outlined in section 6.2. A check of shrinkage limit values was not made. Test results showed that the Atterberg limits had not changed over this seventy-two hour period. Thomson (1960) found that the plastic and liquid

limits for non-homionic soils varied appreciably for periods of up to thirty-three days after mixing. The soil solution used in Thomson's work, however, contained extraneous cations as his method of preparation did not include removal of cations from the pore solution. It was concluded by Thomson that cations were being continually exchanged between the soil and soil solution until chemical equilibrium was finally achieved. Up to this equilibrium time variations in Atterberg limits were observed.

For the present investigation, homionic soils were used and distilled water was employed as pore fluid. Thus, it was concluded that no time effect could occur as a result of the exchange of cations between the soil and pore solution. However, it is feasible that a long term change might occur after the addition of water to the sample. This possible change in the limits with time could be caused by the slow growth of water hulls around the adsorbed cations. This slow completion of cation hydration is to be expected in a highly impervious clay soil which contains a large percentage of montmorillonite and when a large soil to solution ratio of, say, 1:1 is used.

The results of the Atterberg limit tests for the homionic clays and for the natural clay are listed in table 3 and are plotted for comparison purposes on plate 7. (From this data, it can be seen that the Ca^{++} and the Mg^{++} cation have little effect on the plasticity characteristics of the clay, when compared to the natural soil. The shrinkage limit of the natural soil

SOIL TYPE	ATTERBERG LIMITS				
	LIQUID LIMIT	PLASTIC LIMIT	PLASTIC INDEX	SHRINKAGE LIMIT	SHRINKAGE RATIO
Natural Clay	76.1	28.9	47.2	9.7	1.80
Homionic Ca-Clay	79.7	31.0	48.7	12.3	1.83
Homionic Mg-Clay	79.2	30.1	49.1	14.3	1.82
Homionic Na-Clay	95.7	26.4	69.3	13.8	1.78
Homionic K-Clay	69.5	32.6	36.9	17.2	1.73

ATTERBERG LIMIT TESTS ON
NATURAL AND HOMIONIC
SOILS

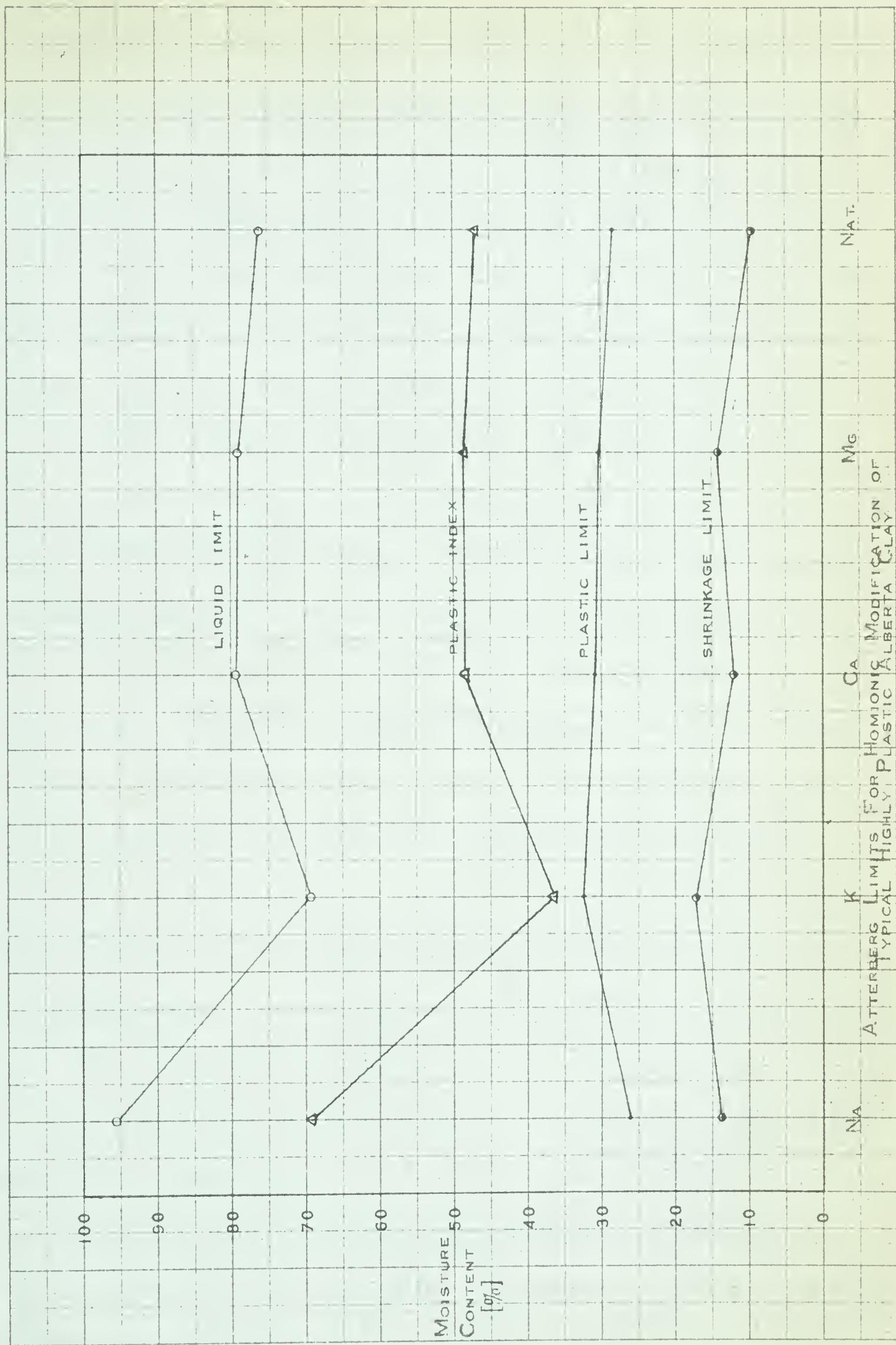
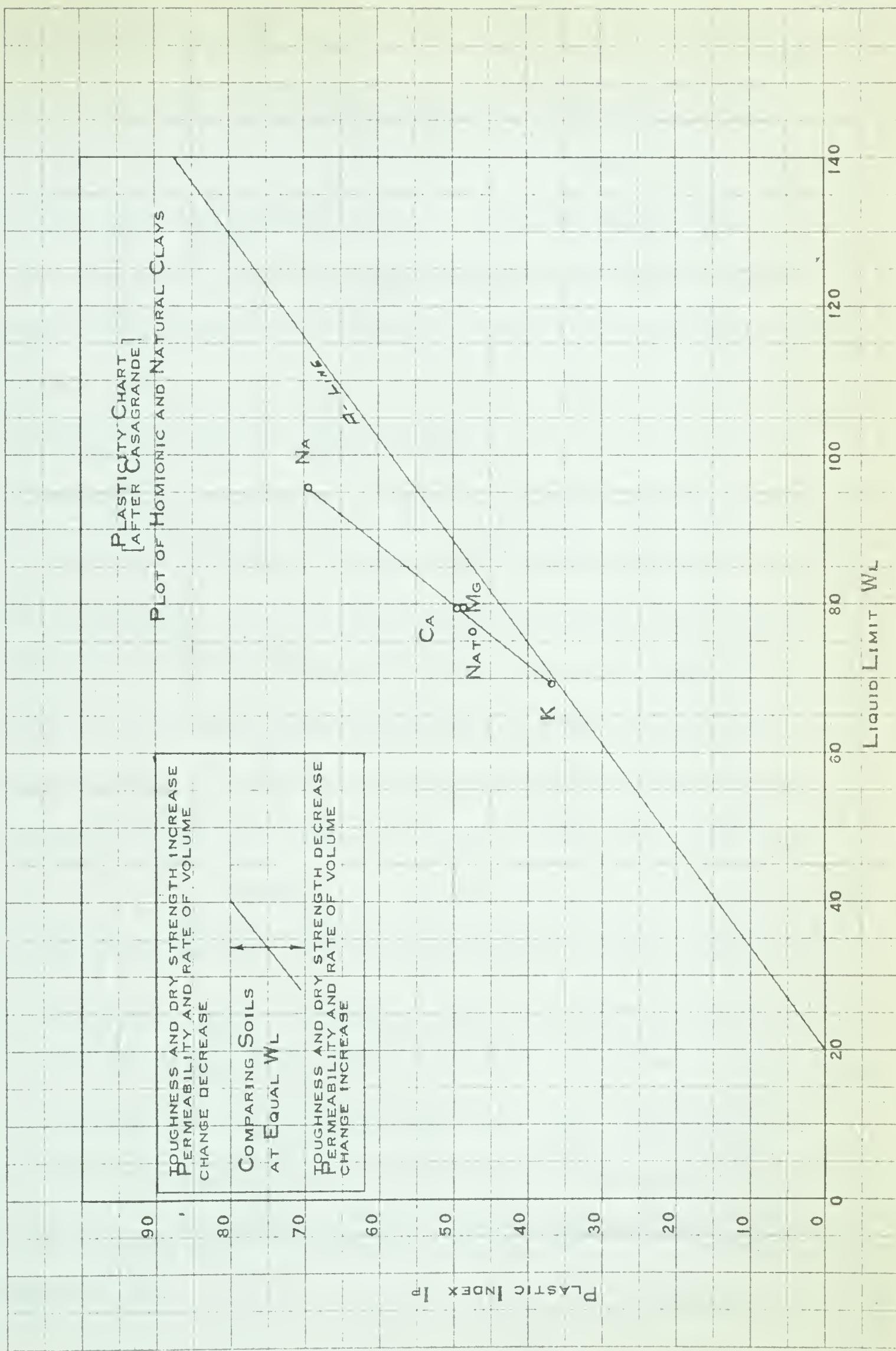


PLATE 7

was found to be slightly less than that of the homionic Ca^{++} and Mg^{++} clays. The sodium cation, however, caused great changes in the plasticity characteristics, raising the liquid limit by about 26% and lowering the plastic limit. This increase in liquid limit and decrease in plastic limit resulted in a relatively large increase in the plastic index of the Na^+ -clay over that of the natural clay. The potassium soil, on the other hand, showed a decrease in the liquid limit and an increase in the plastic limit which resulted in a lower plastic index than for the natural clay.

The test results for the four homionic clays and the natural clay were plotted on the Casagrande plasticity chart (plate 8). It has been found by Coates (1954), that homionic modifications for Leda clay plotted as a straight line, parallel to the A - line on the plasticity chart. This present investigation indicated a straight line relationship which was not parallel to the A - line. By comparing the distance above the A - line for each point, it was predicted that the homionic Na^+ -clay should exhibit greater dry strength and toughness and lower permeability and rate of volume change than the natural soil. The K^+ -clay plotted closer to the A - line than did the natural clay and hence it was indicated that the K^+ clay should exhibit less toughness and dry strength and greater permeability and rate of volume change than the natural clay. The data for the Ca^{++} and Mg^{++} -clays plotted close to the natural clay and hence it was decided that the behaviour of these clays should be similar to that of the natural clay.

The variations in Atterberg limits with type of adsorbed cation that were observed for the highly plastic Edmonton clay agreed reasonably well with the test results obtained by Winterkorn and Moorman (1941) on beidellite clay (plate 2) and by Cornell University (1951) on montmorillonite



(plate 3). The results of Thomson's work (1960) on non-homionic samples of Alberta clay shales (plate 5) also agree quite favorably with the test results from the present investigation except for a difference in the variation of the liquid limit for the K^+ -clays. Thomson indicated that both the liquid limit and plastic limit of K^+ -clay are greater than that of the natural soil, while this investigation showed that the liquid limit is decreased and plastic limit is increased when potassium is added to the natural clay.

6.4.2 Consolidation Tests - Homionic Soils

After total exchange capacity tests, flame tests and Atterberg limit tests had been performed on each homionic clay sample, the remaining air dried soils were mixed with distilled water to moisture contents close to the liquid limit and the samples were then placed in the moist room for a period of seventy-two hours to allow complete dispersion of moisture. Consolidation tests on each homionic soil sample were then carried out by the method outlined in section 6.2. For these tests, the 1.0 inch deep consolidation ring was filled to a depth of 0.9 inches by using a spacer disc which was removed after the ring was filled. For the potassium clay, the sample used was only 0.75 inches in depth. Consolidation test data sheets for the homionic soils are enclosed in Appendix B.

It was found that the remoulded homionic sodium clay swelled appreciably under the initial pressure of 0.07 kg/cm^2 when water was added to the consolidation dish (see dial reading - time curves homionic Na^+ clay, Appendix B).

The "swelling pressure" for the homionic Na^+ clay was obtained by allowing the sample to swell in the presence of water under the initial pressure of 0.07 kg/cm^2 . Further load increments were added and the pressure at which the void ratio of the sample became equal to the initial void ratio through consolidation, was taken as the swelling pressure of the clay. The swelling pressure exerted by the homionic sodium soil was found to be approximately 0.16 kg/cm^2 . No initial swelling was noted for the homionic calcium, magnesium, potassium or natural soils.

The compressive index (C_c) for each sample was calculated from the slope of the straight line portion of the $e - \log p$ curves. C_c for the potassium clay was found to be slightly less than that for the natural clay, while the C_c 's for the calcium and magnesium soils were approximately the same, but were greater than that of the natural soil. The compressive index of the sodium soil was found to be much greater than that of the natural clay; indicating that the sodium clay is the most compressible of the five types of soil tested.

The swelling index was determined for each soil modification by calculating the increase in void ratio for the unload or rebound portion of the $e - \log p$ curves from 1.0 to 0.1 kg/cm^2 pressure. Although this portion of the curve is not usually a straight line, the approximate slopes so calculated are useful for comparison purposes. Little difference was found in the swelling indices of the natural, magnesium, potassium and calcium clays. The swelling index of the sodium clay was found to be approximately four and one-half times greater than that of the natural soil, indicating that a sodium

clay would swell under a decrease in pressure (when water is present) to a much greater degree than would homionic calcium, potassium or magnesium clays.

The coefficient of permeability of each sample was calculated from the consolidation data for the 0.60 to 1.18 kg/cm² load increment. It was found that the calcium clay was slightly less permeable and the magnesium clay slightly more permeable than the natural soil. The potassium soil was found to be about one-third as permeable as the natural soil, while the sodium clay was found to be approximately one-tenth as permeable as the natural clay.

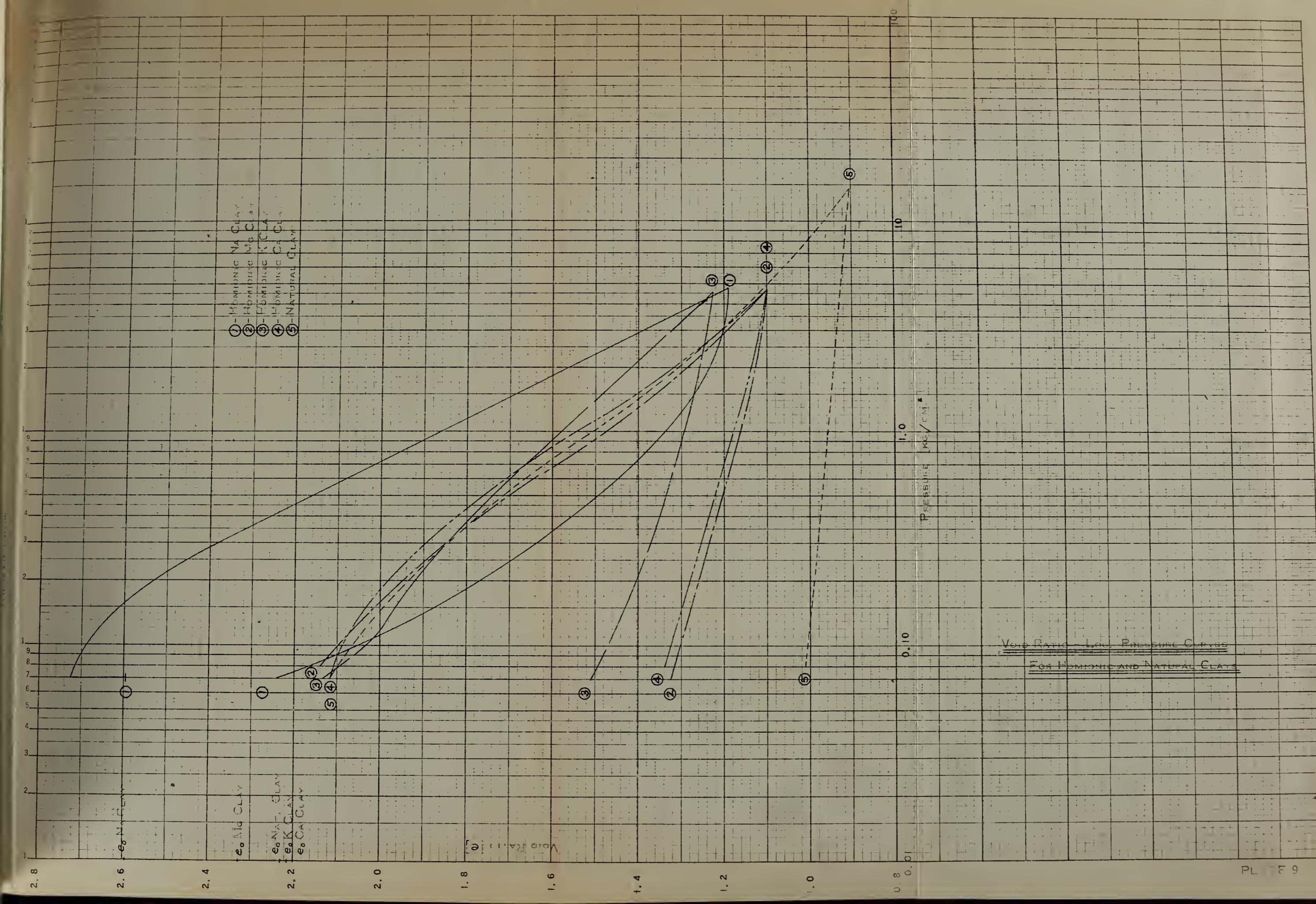
The void ratio of each soil modification was calculated for the 0.60 - 1.18 kg/cm² pressure increment by averaging the initial and final void ratios for this increment. The void ratios for the natural clay, the homionic calcium clay, the homionic magnesium clay and the homionic potassium clay were found to show little variation under this pressure. However, the homionic sodium clay exhibited a much higher void ratio than that of the natural clay.

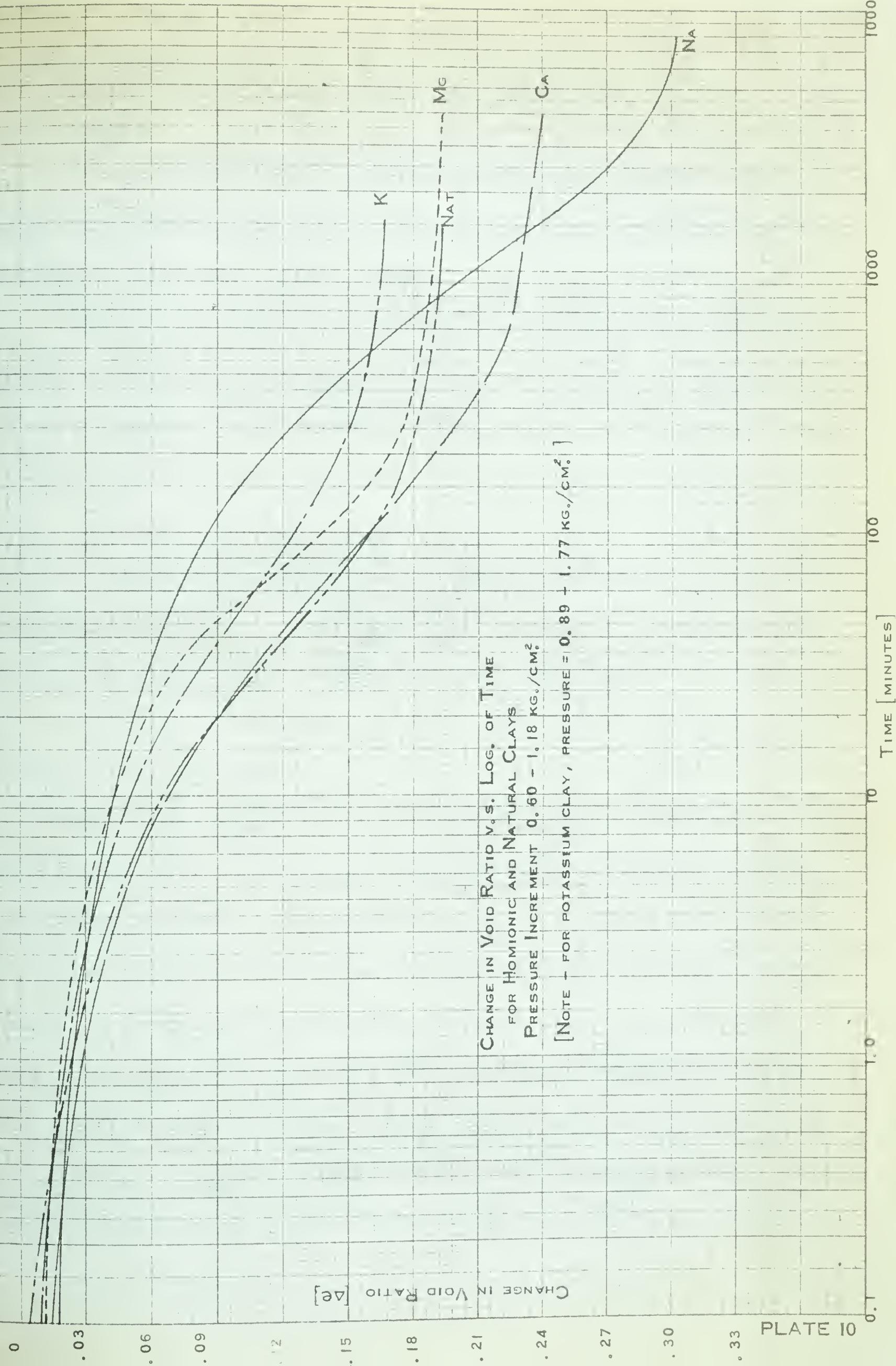
The consolidation data for the homionic and natural clays is summarized in table 4 and $e - \log p$ curves and $\Delta e - \log t$ curves for the 0.60 - 1.18 kg/cm² pressure increment are plotted on plates 9 and 10 respectively. Appendix B contains the test data sheets for the homionic clay modifications.

Soil Type	Compressive Index (Cc)	Coefficient of Permeability k (cm/sec)*	Swelling Pressure (kg/cm ²)	Swelling Index	Molding Moisture Content (%)	Liquid Limit	Void Ratio (e)**
Natural Clay	0.54	1.44×10^{-8}	0	0.16	79.9	76.1	1.44
Homionic Ca ⁺ -Clay	0.68	1.15×10^{-8}	0	0.14	72.5	79.7	1.60
Homionic Mg ⁺ -Clay	0.63	1.63×10^{-8}	0	0.15	69.1	79.2	1.56
Homionic Na ⁺ -Clay	0.93	0.12×10^{-8}	0.16	0.74	92.0	95.7	1.93
Homionic K ⁺ -Clay	0.50	0.37×10^{-8}	0	0.18	75.3	69.5	1.61

* k values shown are for 0.60 - 1.18 kg/cm² pressure increment
 ** e values shown are average values for 0.60 - 1.18 kg/cm² increment

SUMMARY OF CONSOLIDATION TEST DATA
 HOMIONIC AND NATURAL SOILS





6.5 Preparation of Sodium - Calcium Clay Modifications

6.5.1 General

Winterkorn (1941) has shown that the addition of small amounts of sodium to a predominantly calcium-clay will result in the clay exhibiting the properties of an homionic sodium-clay.

Grim (1952) states that in Na^+ systems, montmorillonite and possibly other clay minerals are tied together mostly at the edges and a dispersed soil structure results. In Ca^{++} systems, bonding is greater from basal surface to basal surface. In cases where Ca^{++} is at least equal to the exchange capacity, a flocculated structure is formed with one flake on top of another.

However, when the concentration of Ca^{++} is less than the exchange capacity and small amounts of Na^+ are present, the bonding properties are changed. Thus, according to Grim, a small amount of replacement of Ca^{++} by Na^+ can cause a great shift in particle bond with a corresponding great change in the physical properties.

Initial tests on the natural clay used in this investigation indicated that the majority of the cations adsorbed were calcium with lesser amounts of magnesium, sodium and potassium also present (see table 1). It was also shown that the natural clay exhibited plasticity and consolidation characteristics which were approximately the same as those for an homionic calcium modification of the same clay. Thus, it may be stated that the natural clay is, in fact, a calcium clay and that the lesser amounts of sodium, potassium and magnesium present do not appreciably alter the physical properties of the clay. It has been shown that an homionic sodium clay exhibits

vastly different physical properties from those of an homionic calcium clay and it was decided that an investigation of the effects of sodium (in varying quantities), on an initially calcium-saturated clay should be carried out. It was decided to produce homionic calcium clays as the first step, and then, by chemical means, exchange some of these calcium cations with sodium cations. In this way, soils having different proportions of calcium and sodium adsorbed were produced and engineering tests were performed on the resulting modifications.

6.5.2 Method Used

Two thousand grams of air dried natural clay was transformed into homionic calcium clay by the method outlined in section 6.3.3. This clay was maintained in an air dry state and stored in glass sealers, 200 grams to each sealer, until needed.

Kelly (1948) has shown that the concentration of the solution used to cause cation exchange has a marked effect on the exchange reaction. He has shown that for cations of different replacing power and different valence such as Na^+ versus Ca^{++} , dilution of the solution produces a decrease in the amount of Na^+ that will replace exchangeable Ca^{++} on the clay particles. In order to determine the normality of the sodium acetate solution required to cause a given amount of Na^+ cations to be adsorbed on the clay, pilot tests were run on eight - five gram samples of homionic Ca^{++} -clay.

The samples were treated in the following manner: Each sample was placed in a 100 ml. centrifuge tube and fifty cc. of sodium acetate solution was added. Thus a soil-solution ratio of 1 to 10* was used.

* A soil-solution ratio of 1:10 refers to a mixture of 1 gram of air dried soil in ten cc. of NaAc solution.

The normalities of the NaAc solution used were as follows:

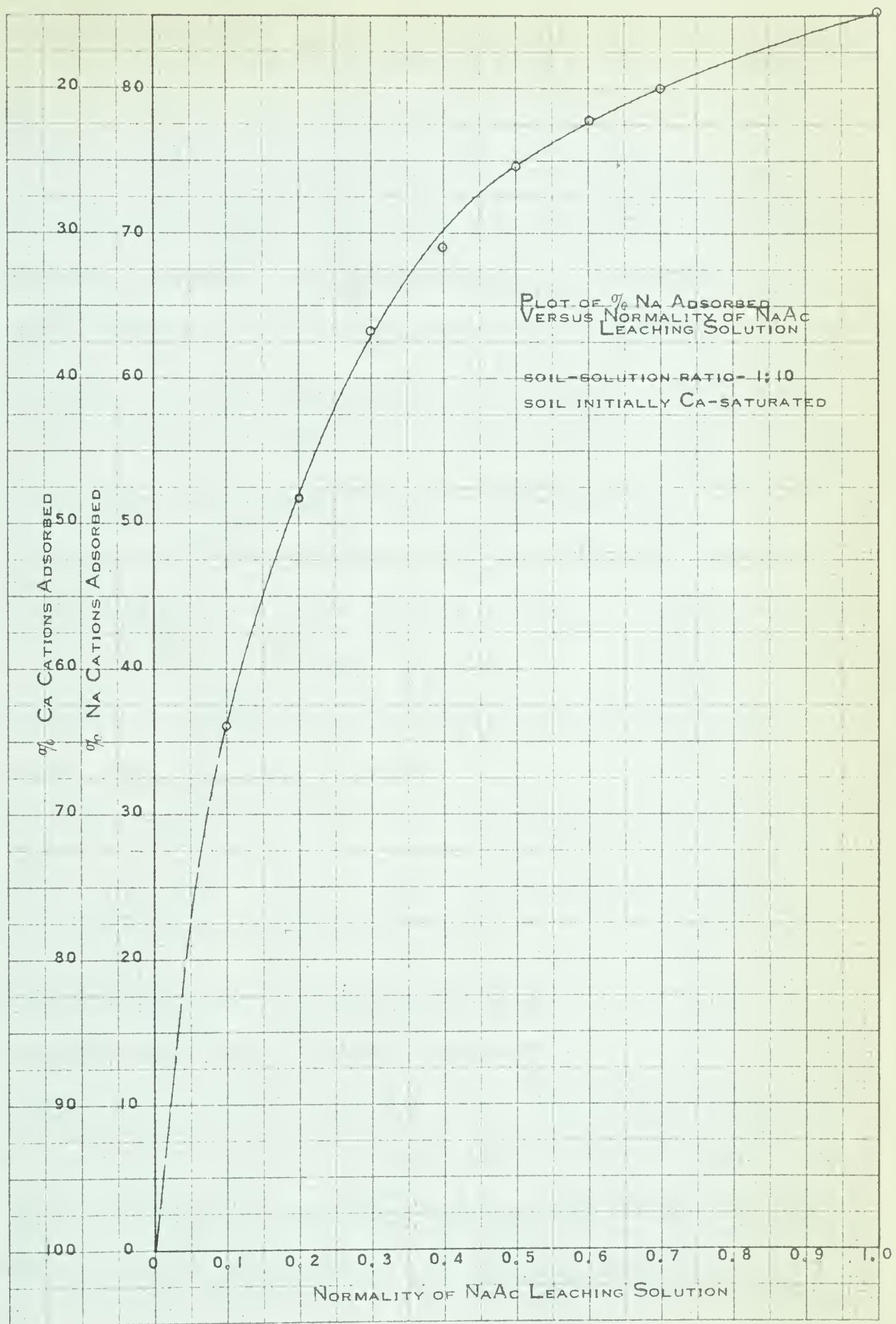
<u>Sample Number</u>	<u>Normality</u>
1	1N
2	.7N
3	.6N
4	.5N
5	.4N
6	.3N
7	.2N
8	.1N

The soil and solution were then mixed for two minutes with an electric milk-shake mixer and allowed to stand for a time interval of one hour to achieve equilibrium. The sodium acetate was then removed from solution by centrifuging the samples, decanting the supernatant liquid and then centrifuging the samples three more times using methyl and ethyl alcohol as the rinsing medium. The samples were then allowed to air dry, and flame photometer tests were performed to determine the amounts of Na^+ and Ca^{++} cations adsorbed. The results of the flame photometer tests are shown in table 5 and plate 11.

From plate 11, the normality of NaAc solution required to produce a clay having any given percentages of Na^+ and Ca^{++} cations adsorbed can be determined approximately. This chart was used to determine the normality of the leaching solution to be used with the test samples. Two thousand cc. of the desired leaching solution was added to each 200 grams of homionic calcium clay, (soil - solution ratio 1:10) and the resulting mixture was mixed for two minutes with an electric mixer and allowed to stand for one hour. The supernatant liquid was syphoned off and the mixture was poured into centrifuge tubes and centrifuged to remove most of the excess

Sample No.	Normality of NaAc Leaching Solution	Ca ⁺ Cations me/100g	Na ⁺ Cations me/100g	Total	%Ca ⁺⁺	%Na ⁺
1	1.0N	4.0	24.0	28.0	14.3	85.7
2	0.7N	5.5	22.0	27.5	20.0	80.0
3	0.6N	6.0	21.0	27.0	22.2	77.8
4	0.5N	7.5	22.0	29.5	25.4	74.6
5	0.4N	9.0	20.0	29.0	31.0	69.0
6	0.3N	11.0	19.0	30.0	36.7	63.3
7	0.2N	14.0	15.0	29.0	48.3	51.7
8	0.1N	19.5	11.0	30.5	64.0	36.0

VARIATION IN PERCENT OF ADSORBED
 Na⁺ WITH CHANGE IN NORMALITY
 OF NaAc SOLUTION



NaAc and the replaced Ca^{++} cations. The samples were then rinsed by centrifuging three more times with methyl and ethyl alcohol, and allowed to air dry.

By using plate 11 to determine normalities of the NaAc leaching solutions, eight samples were prepared, each having a different percentage of sodium cations adsorbed. The samples were then tested with the flame photometer to determine the type and quantity of adsorbed cations. Table 6 shows the percent Na^+ adsorption, which was anticipated, as based on the results of the pilot tests and also shows the percent Na^+ adsorption achieved on the test samples, as determined by flame photometer tests.

For low normalities, it was found that the actual percent sodium adsorption deviated from the values indicated by plate 11. This may be explained by the fact that below 36% Na^+ adsorption, the curve on plate 11 was extrapolated and normalities were chosen by using this extrapolated portion of the curve which may be in error.

After each 200 gram sample of clay was treated and then air dried, the clay was ground down to pass a number 40 sieve, sealed in a quart sealer and stored until required for testing.

6.6 Testing of Sodium - Calcium Soil Modifications

6.6.1 Atterberg Limit Tests - Na-Ca Modifications

Liquid limit, plastic limit and shrinkage limit tests were performed on five of the eight sodium-calcium clays. The samples tested were #1, #2, #6, #7 and #8 (see table 6). One hundred grams of each sample was mixed with distilled water to a moisture content close to the liquid limit and after

CHART SHOWING NORMALITY OF NaAc LEACHING
SOLUTION AND PERCENT Na⁺-ADSORPTION
ACHIEVED FOR TEST SAMPLES

Sample No.	Exchangeable Cations Anticipated (based on plate 11)	Actual Exchangeable Cations Na ⁺ %	Ca ⁺⁺ %	Na ⁺ %	Ca ⁺⁺ %	Normality of NaAc Treatment Solution (based on plate 11)
1	2	98		5.8	94.2	0.01
2	5	95		13.9	86.1	0.02
3	10	90		15.1	84.9	0.025
4	15	85		16.8	83.2	0.035
5	20	80		20.1	79.9	0.05
6	25	75		28.4	71.6	0.06
7	50	50		54.4	45.6	0.20
8	75	25		77.9	22.1	0.50

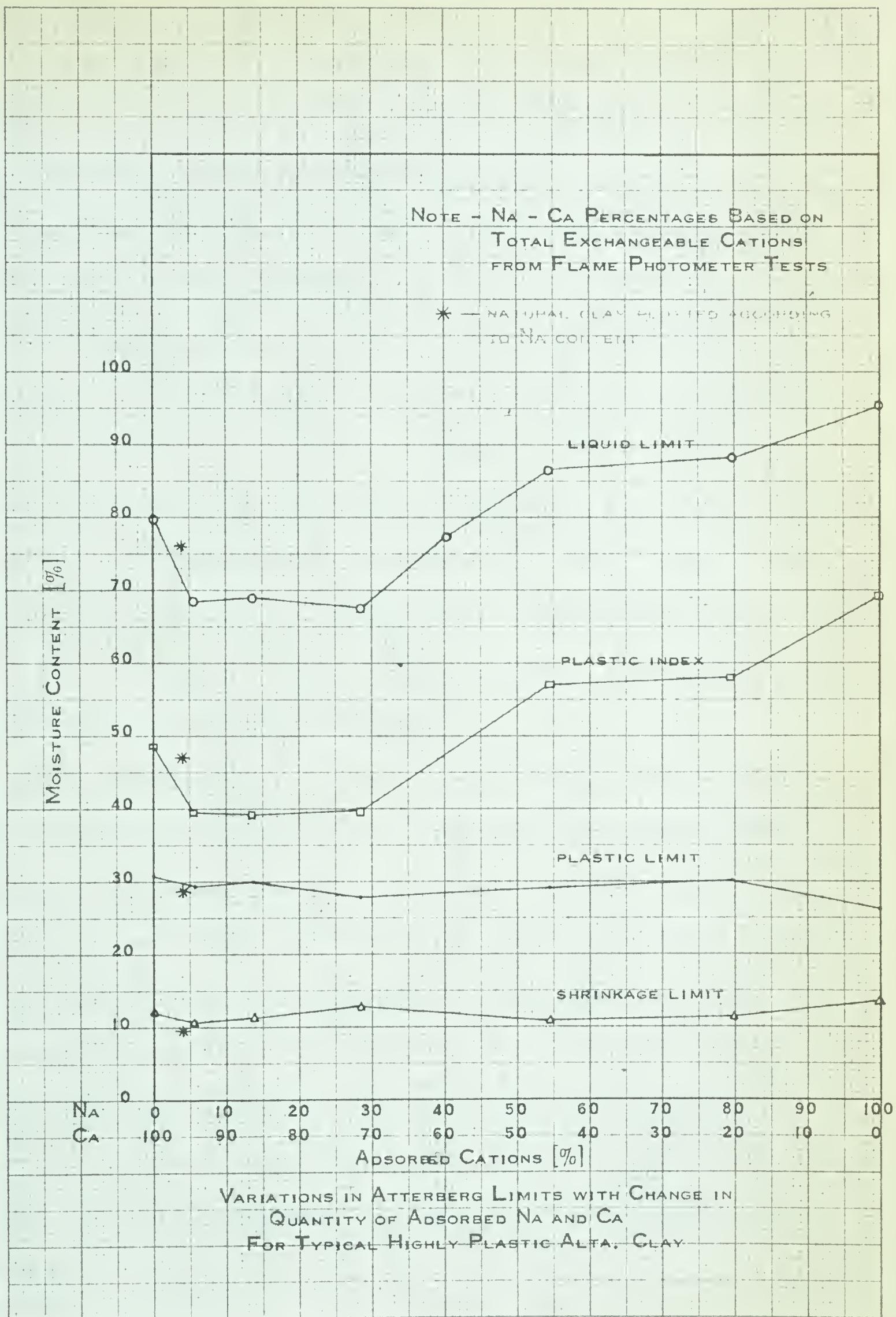
the sample had been in the moist room for forty-eight hours, the Atterberg limit tests were performed by the method described in section 6.2. Check tests were run seventy-two hours after mixing by using the one-point liquid limit procedure with an assumed value of Tan B of 0.121. It was found that no significant change in the liquid limit occurred over this time interval for any of the Na-Ca clay modifications. The results of the Atterberg limit tests are listed in table 7 and are plotted for comparison purposes on plate 12.

It was found that the addition of a small amount of sodium caused appreciable changes in the liquid limit of the initially calcium saturated soil. With the addition of only 5.8% Na^+ cations, the liquid limit of the clay decreased 10% from that of the homionic calcium clay. Further increases in the amount of sodium caused the liquid limit to decrease slightly and a liquid limit of 12% less than the homionic calcium clay was reached at 28.4% sodium adsorption. Further increases in the amount of adsorbed Na^+ cations caused an increase in the liquid limit of the clay (see plate 12). Little change was observed in both the shrinkage and plastic limits with an increase in the amount of Na^+ adsorbed on the clay and thus the plastic index, in general, showed the same trend as the liquid limit for all modifications.

For comparison purposes, the Atterberg limits of the natural clay were also plotted on plate 12 according to Na^+ content. As the adsorbed cations on the natural soil were found to be mainly Ca^{++} and Mg^{++} with approximately 4% Na^+ cations and a lesser amount of potassium cations, it was decided that the soil would behave much like a calcium soil with 4% Na^+

SOIL TYPE	ATTERBERG LIMITS			
	LIQUID LIMIT	PLASTIC LIMIT	PLASTIC INDEX	SHRINKAGE LIMIT
Homionic CaClay	79.7	31.0	48.7	12.3
94.2%Ca-5.8% NaClay	68.7	29.5	39.2	10.8
86.1%Ca-13.9% NaClay	69.1	30.0	39.1	11.3
71.6%Ca-28.4% NaClay	67.5	28.0	39.5	13.0
59.9%Ca-40.1% NaClay	77.2	-----	-----	-----
45.6%Ca-54.4% NaClay	86.3	29.1	57.2	10.8
22.1%Ca-77.9% NaClay	88.2	30.2	58.0	11.3
Homionic NaClay	95.7	26.4	69.3	13.8

ATTERBERG LIMIT TESTS ON
Na - Ca MODIFICATIONS



cations adsorbed. It was found that the plotted points agreed reasonably well with the established curves for the Na-Ca clay modifications (see plate 12).

6.6.2 Consolidation Tests - Na-Ca Modifications

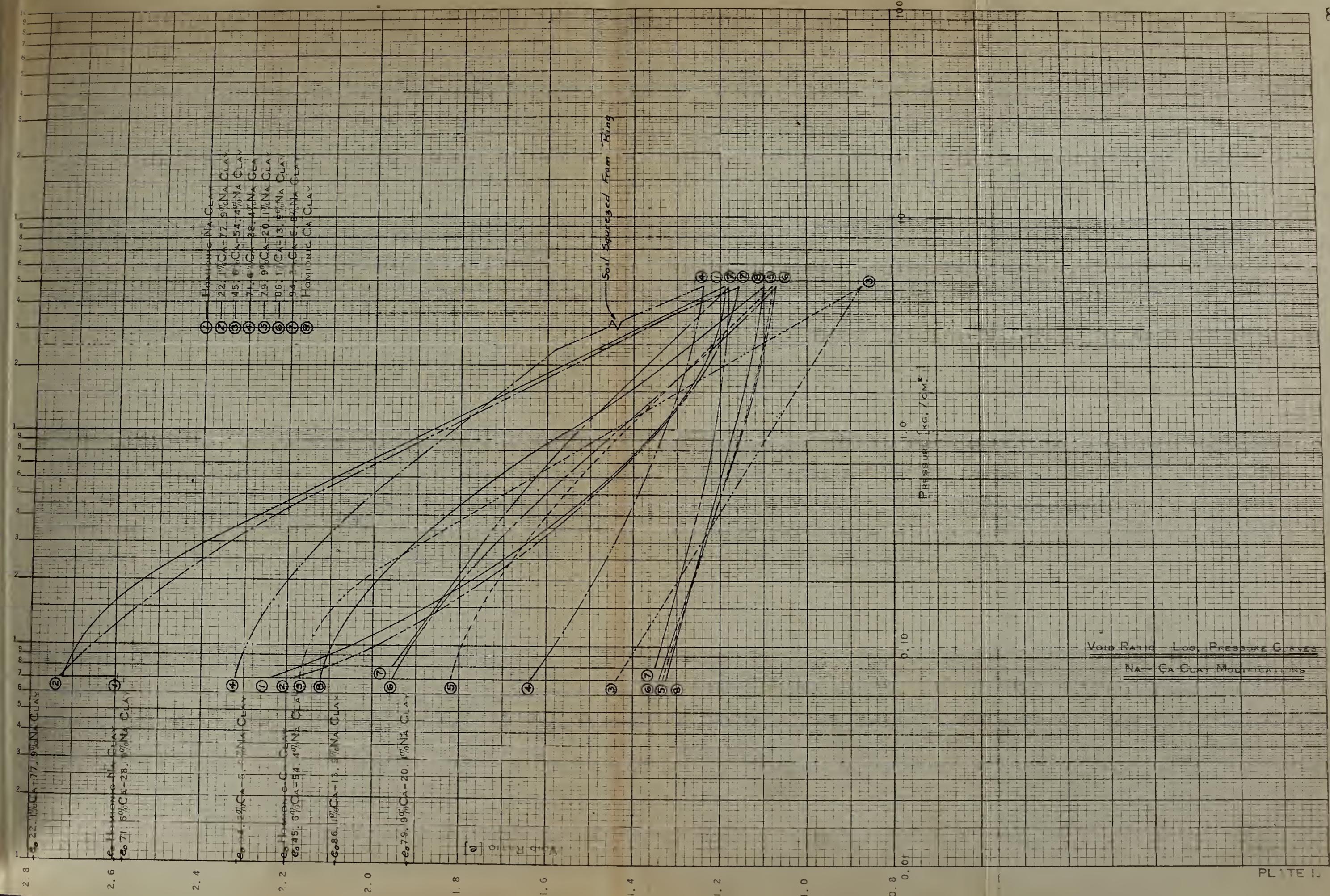
Approximately 100 grams of each modified clay remained after the Atterberg limit tests had been performed. These air dried soils were mixed with water to approximately the liquid limit and consolidation tests were performed on the remoulded soils by the method outlined previously in section 6.2. Each sample was loaded in increments to a final pressure of 4.6 kg/cm^2 and rebounded in two steps to a pressure of 0.07 kg/cm^2 . The results of the consolidation tests are summarized in table 8 and void ratio - log. of pressure curves are plotted on plate 13. Consolidation - time curves for the $0.60 - 1.18 \text{ kg/cm}^2$ pressure increment and test data sheets for each clay modifications are found in Appendix C.

The compressive index for each clay modification was calculated from the straight line portion of the $e - \log p$ curve. In some instances, this curve exhibited no definite straight line portion and an average "best-fit" straight line was used for calculating the compressive index. A striking feature of these tests was the sudden drop in compressive index of the clay which occurred with only a small amount of replacement of Ca^{++} by Na^+ . After this initial drop, no significant increase in the C_c was experienced with further increases in adsorbed Na^+ up to about 28%. Beyond 28% Na^+ adsorption, the compressive index increased with further increases in the amount of Na^+ .

SOIL MODIFICATION	Compressive Index (Cc)	Coeff. of Permeability k(cm/sec)*	Swelling Pressure ² kg/cm ²)	Swelling Index	Molding Moisture Content %	Liquid Limit	Void Ratio (e)**
Homionic Ca ⁺⁺ Clay	0.68	1.15x10 ⁻⁸	0	0.14	72.5	79.7	1.60
94. 2%Ca-5. 8% Na	0.51	0.97x10 ⁻⁸	0	0.12	80.0	68.7	1.54
86. 1%Ca-13. 9% Na	0.53	0.40x10 ⁻⁸	0	0.17	69.2	69.1	1.48
84. 9%Ca-15. 1% Na	0.55	0.50x10 ⁻⁸	0	0.16	84.1	----	1.51
79. 9%Ca-20. 1% Na	0.50	0.25x10 ⁻⁸	0	0.16	62.1	----	1.45
71. 6%Ca-28. 4% Na	0.58	0.13x10 ⁻⁸	0	0.27	100	67.5	1.87
45. 6%Ca-54. 4% Na	0.82	0.10x10 ⁻⁸	0	0.31	86.2	86.3	1.50
22. 1%Ca-77. 9% Na	0.96	0.08x10 ⁻⁸	0	0.70	101.0	88.2	1.92
Homionic NaClay	0.98	0.12x10 ⁻⁸	0.16	0.74	92	95.7	1.93

* k values shown are for 0.60 - 1.18 kg/cm² pressure increment
 ** e values shown are average values for 0.60 - 1.18 kg/cm² increment

SUMMARY OF CONSOLIDATION TEST
 DATA NaCa CLAY MODIFICATIONS



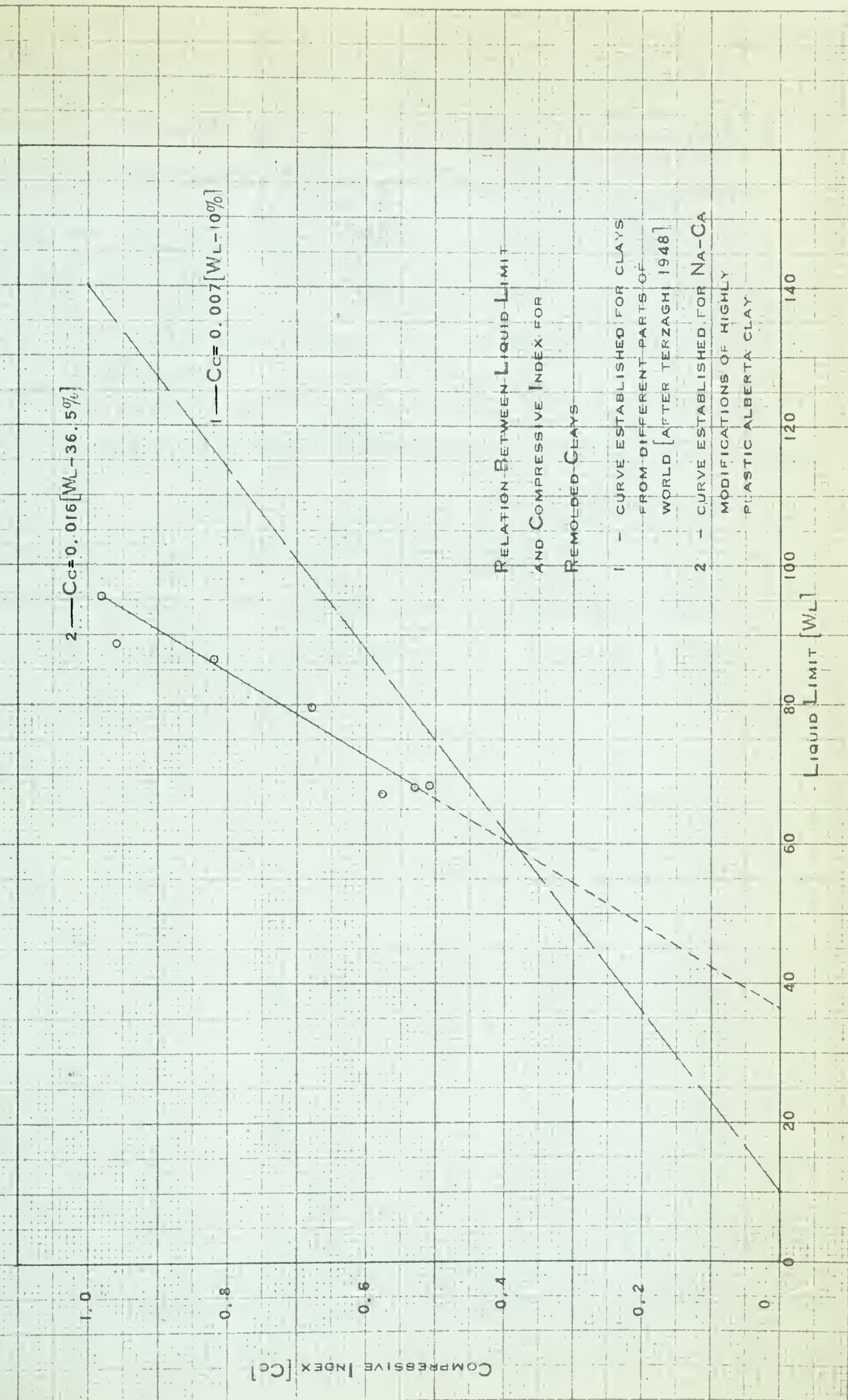
Void ratios were calculated for each sample by averaging the initial and final void ratio for the $0.60 - 1.18 \text{ kg/cm}^2$ pressure increment. The same trend was evident as was found for the compressive indices-- an initial drop in void ratio occurred with the addition of a small amount of Na^+ ; the void ratio then remained approximately constant up to approximately 28% Na^+ adsorption, beyond which further increases in Na^+ caused a corresponding increase in void ratio. The changes in void ratio and compressive index generally followed the same trend as was exhibited by the liquid limit for the Na-Ca clay modifications (see plate 12).

No swelling pressure was exhibited by any of the Na-Ca clay modifications.

The coefficient of permeability, k , for each sample, was calculated for the $0.60 - 1.18 \text{ kg/cm}^2$ pressure increment and it was found that permeability decreased with increased Na^+ adsorption on the clay.

The swelling indices calculated for the 0.1 to 1.0 kg/cm^2 portion of the $e - \log p$ curves, in general, increased with an increase in the amount of Na^+ adsorbed on the clay.

Terzaghi (1948) indicated a relationship between W_L and C_C for samples of remolded clays from different parts of the world. He found that a plot of C_C versus W_L resulted in a number of points which were close to a straight line with the equation, $C_C = 0.007 (W_L - 10\%)$. The scattering of the C_C values for his plot was about ± 30 percent. Plate 14 shows this straight line which covers a range of W_L from about 20 to 130. The test data from the present investigation of the Na-Ca modification of a highly plastic Alberta clay, were



plotted on this plate for comparison purposes and a straight line was drawn through the plotted points. The equation of this line was found to be, $C_C = 0.016 (W_L - 36.5\%)$. The range of liquid limit for these modifications was from approximately 66 to 96. Although the equation of the two lines did not agree, it was indicated that the C_C values for the Na-Ca clays increased with increasing liquid limit. The difference in equations 1 and 2 is most probably due to the W_L of the test specimens covering only a small portion of the total range in liquid limit which was used in determining equation 1. However, it must be pointed out that the data for curve 2 has been derived from a single soil sample. If many soil samples covering a wide range in liquid limits had been tested, it is probable that a line in close agreement with that of Terzaghi would have been determined.

CHAPTER 7

SUMMARY AND DISCUSSION OF TEST RESULTS7.1 Effects of the Adsorbed Cation on Shrinkage and Swelling

For the highly plastic Edmonton clay tested, it was found that no significant change in the shrinkage limit occurred with a change in the adsorbed cation.

The swelling index for calcium and magnesium clays was approximately the same as that for the natural clay. The sodium cation caused the swelling index to increase to approximately four and one-half times more than that of the natural clay. The potassium cation produced only a slight increase in the swelling index of the clay.

An interesting effect observed during the course of the investigation was the 0.16 kg/cm^2 swelling pressure exerted by the homionic sodium consolidation sample. The sample was remoulded at a moisture content of 92%, which is very close to the liquid limit for this clay (95.7%). It is difficult to explain this initial swelling as most remoulded clays at moisture contents close to the liquid limit do not tend to take up more water and swell when tested. It was concluded that for the homionic sodium clay, a moisture content of 92% was not sufficient to ensure complete hydration of the adsorbed sodium cations. After the sample had been placed in the consolidometer and covered with distilled water, completion of the adsorbed water hulls around the adsorbed cations occurred by water migrating into the soil structure from the consolidation dish. As the diameter of the water hulls increased, expansion of the

sample occurred, resulting in the clay exhibiting an appreciable swelling pressure. The dial reading - time curve for the 0 - 0.07 kg/cm² pressure increment is enclosed in Appendix B. This curve shows that swelling did not commence until approximately 2400 minutes or two days after the initial load had been applied, indicating that the low permeability of the soil caused a low rate of migration of water into the soil sample.

No initial swelling pressure was exhibited by the other homionic clay specimens tested.

For the sodium-calcium clay modifications, it was found that with 5.8% sodium and 94.2% calcium cations adsorbed, the swelling index decreased slightly from that of the homionic calcium clay. Increases in sodium over the range of from 5.8% to 20.1% of the total exchange capacity, caused no significant changes in the swelling index. With further increases in adsorbed sodium above 20.1%, the swelling index increased.

7.2 Effects of the Adsorbed Cation on Plasticity Characteristics

The calcium and magnesium cations did not affect the liquid limit or plasticity index of the clay. The sodium cation caused the greatest increase in the plasticity index of the soil by greatly increasing the liquid limit and decreasing slightly the plastic limit. The potassium cation caused a lowering of the liquid limit and an increase in the plastic limit and these two effects caused the plasticity index of the homionic potassium soil to be lower than that of the natural clay.

For the sodium-calcium clay modifications, it was found that an increase in the amount of exchangeable sodium cations had little effect on the plastic limit. With only 5.8% sodium adsorbed, the liquid limit decreased substantially from that of a homionic calcium clay. With further increases in sodium, up to approximately 28.4%, the liquid limit remained essentially constant. With sodium percentages greater than 28.4, the liquid limit increased and at approximately 45% it was equal to that of a homionic calcium clay. Further increases in the amount of sodium adsorbed caused the liquid limit to increase and approach the liquid limit for homionic sodium clay.

7.3 Effects of the Adsorbed Cation on Permeability

The calcium cation decreased the permeability of the clay slightly and the magnesium cation slightly increased the permeability over that of the natural soil. Both sodium and potassium decreased the permeability of the clay. The homionic sodium clay was approximately one-tenth as permeable and the homionic potassium clay about one-third as permeable as the natural clay.

For the sodium-calcium clay modifications, it was found that an increase in the amount of adsorbed sodium caused a progressive decrease in the permeability.

7.4 Effects of the Adsorbed Cation on Consolidation Characteristics

Both calcium and magnesium cations caused a similar small increase in the compressive index. The sodium cation caused the compressive index to increase to almost twice that of the natural clay. The

potassium cation lowered the compressive index slightly.

For the sodium-calcium clay modifications, the changes observed in the compressive indices with increases in the amount of adsorbed sodium, followed the same general trend as did the liquid limits for these soils. The addition of a small amount of exchangeable sodium caused a sudden initial decrease in the compressive index. With increasing amounts of sodium to approximately 28% of the total cation exchange capacity, no significant change in C_c was observed. With sodium contents greater than 28% of the exchange capacity, the compressive index increased with increasing sodium adsorption.

Inspection of the $e - \log p$ curves for the consolidation test specimens showed that the virgin compression branches for the homionic potassium and sodium clays were straight lines. The homionic calcium clay, homionic magnesium clay, and the natural clay, however, consolidated along gently curving "S-shaped" virgin compression lines, possibly indicating the formation of a structure which is broken down when subjected to loading.

It was observed that changes induced in the liquid limit of the highly plastic Alberta clay through cation exchange were accompanied by changes in the compressive index. A plot of compressive index versus liquid limit showed a straight line relationship between these properties; for the sodium-calcium clay modifications the equation of this straight line was calculated as $C_c = 0.016 (W_l - 36.5\%)$.

7.5 Discussion of Test Results

On the basis of the test results, it is possible to divide the cations into two groups, according to their effects on the physical properties of soils. These two groups may be titled flocculants and dispersants. According to Lambe(1954), flocculating cations markedly increase soil porosity and permeability and reduce cohesiveness. Dispersing cations cause high fluidity at low water contents, low permeability and more than normal consolidation.

The homionic calcium and magnesium clays exhibited relatively high permeability, low compressibility, low plasticity and small amounts of shrinkage and swelling as compared to the homionic sodium clay. A comparison of the void ratios at equal pressure showed that the calcium and magnesium clays consolidated to a much smaller void ratio than did the homionic sodium clay. During the course of the investigation, it was observed that calcium and magnesium soils, when mixed with water, formed floes which settled to the bottom of the container readily. Sodium and potassium clays remained in suspension and a continual movement of soil particles throughout the mixture was noted. These phenomena indicated interparticle attractive forces for the calcium and magnesium soils and interparticle repulsive forces acting in the sodium and potassium clays. As a result of these findings, it may be stated that magnesium and calcium cations produce flocculant soil structures while the sodium cation produces a dispersed soil.

The potassium cation induces some of the effects of a flocculant

and some of a dispersant. The liquid limit and plasticity index of the homionic potassium sample were low and it exhibited the lowest compressive index of all the soils tested. However, the permeability of this clay was low and it swelled more than the calcium or magnesium clays. Baver (1956) treats this cation as a dispersant and attributes its low plasticity characteristics to the relatively thin adsorbed water hull which is formed around this cation. This thin water hull means that less water is necessary to produce plasticity characteristics than is required when sodium is adsorbed on a clay.

It was found that the natural clay generally exhibited similar properties to that of the homionic magnesium and calcium soils, even though small amounts of sodium and potassium were present.

Winterkorn (1952) states that if as little as 15% of the exchangeable cations adsorbed on a clay are sodium, the soil will, in general, behave as a homionic sodium soil. This statement implies a sudden change from a flocculated to a dispersed clay structure must occur with only a small percentage of sodium adsorption. To investigate the effect of the sodium cation on the physical properties of a calcium clay, samples were prepared with varying amounts of sodium adsorbed. Engineering tests on these samples did not substantiate Winterkorn's statement. The addition of small amounts of exchangeable sodium generally caused a trend in the physical properties opposite to that indicated by Winterkorn. Plasticity and compressibility of the samples decreased with the initial addition of small amounts of sodium

instead of increasing. However, the permeability of the soil did show a constant decrease with an increase in the amount of exchangeable sodium present.

According to Grim (1952) a small amount of replacement of calcium by sodium can cause a great change in the bonding between particles with a corresponding great change in the physical properties. The cause of this effect of cations on bonding is not known, but it is believed to be related to the geometric fit and hydration of the ions on the edges and surfaces of the clay mineral.

The following theory is suggested to explain the changes which occurred when increasing amounts of exchangeable sodium was added to a calcium clay. Homionic calcium clay develops a flocculant structure with the clay particles tied together in a random pattern, i. e. the so-called "card-house" structure. According to Grim (1952), the addition of small amounts of sodium causes an end to end linkage of clay particles and the tendency is for the lateral growth of the aggregates and a "parallel" clay orientation results. This change in structure from the "card-house" pattern to the "parallel" pattern would account for the decrease in void ratio, plasticity and compressibility which occurred when small amounts of sodium were introduced. For the samples tested, this change in bonding occurred with less than 6% sodium cations adsorbed. Due to the decrease in void ratio, the permeability would also necessarily decrease. For clays containing montmorillonite, the calcium cation tends to bind the crystal sheets together and at low concentrations of ad-

sorbed sodium, this binding prevents the expansion of the crystal lattice as water is not able to penetrate and fully hydrate any adsorbed sodium cations between the sheets. With further increases in adsorbed sodium, the number of sodium cations between the sheets of the clay minerals increases and at some definite concentration, the hydration of the sodium cations is completed, thereby causing an expansion of the mineral lattice with a corresponding increase in void ratio, plasticity characteristics, and compressibility. For the test samples, these properties began to increase at approximately 28% sodium adsorption. With further increases in the sodium cation, more expansion of the mineral lattices occurs through hydration of these cations resulting in a gradual increase in void ratio, plasticity and compressibility.

Lambe (1957) cites Green who found that the even low concentrations of salt in the pore solution can cause great increases in the liquid limit of a clay. Thomson (1960) investigated cation effects on the physical properties of a northern Alberta clay shale and found that a large increase in the liquid limit and decrease in permeability of the clay occurred with only small amounts of sodium adsorbed. However, the pore solution of the clays contained relatively high concentrations of the sodium cation. The increase in plasticity of the clay with only a small amount of sodium adsorbed may have been caused by the salt concentration in the pore fluid and not by the effects of the adsorbed cation.

The amount of swelling that occurs with a decrease in pressure on the sample is shown by the $e - \log p$ curves (plates 9 and 13). From plate 9 it can be seen that the potassium, calcium, magnesium, and natural clays exhibited more or less similar rebound characteristics. However, the sodium cation caused a great increase in the amount of rebound, as compared to the natural soil -- the sample recovering to a void ratio which was only slightly less than that of the initial void ratio at the beginning of the test (see plate 9). It is interesting to note that this curve is similar to consolidation curves for highly preconsolidated clay shales from northern Alberta. It also resembles consolidation curves obtained for normally consolidated Lake Agassiz clays from Manitoba. Plate 13 shows that as the amount of sodium adsorbed on a clay increases, the amount of swelling or rebound also increases.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS8.1 General Conclusions

- i The physical properties of a soil can be markedly altered through cation exchange.
- ii The effects of the adsorbed cation appears to be related mainly to its influence on the hydration of the soil particles and its effect on the repulsive and attractive forces between the clay particles.
- iii On the basis of present knowledge and existing theories, it is possible to divide cations into two general catagories-- flocculants and dispersants--depending upon their influence on the soil structure. In general, a flocculated soil exhibits lower compressibility, plasticity and swelling than does a dispersed soil.
- iv The cation exchange reaction is exceedingly complex and is influenced by a great number of factors.
- v The practical applications of cation exchange to improve the engineering properties of a soil, have so far been restricted to the treatment of surface deposits such as canal and lagoon linings and base course stabilization. As yet, no method has been devised to treat relatively large volumes of undisturbed soil.

8.2 Conclusions From the Laboratory Investigation

- i Homionic soils may be produced successfully in the laboratory if the soil is leached or washed continuously with a solution containing the desired cation until all extraneous cations have been removed from the soil and pore solution. Producing large quantities of homionic soil in the laboratory does not appear feasible due to the great amount of time and expensive chemicals required.
- ii On the basis of existing theories, it may be stated that the calcium and magnesium cations produce a flocculant soil structure, while the sodium cation produces a dispersed soil structure. The potassium cation, when adsorbed on the highly plastic Alberta clay which was used in the investigation, results in a soil which exhibits some of the characteristics of a flocculated clay and some of a dispersed clay.
- iii For the clay tested, the adsorption of small amounts of exchangeable sodium on a calcium clay does not result in the clay exhibiting the properties of an homionic sodium clay.
- iv It is postulated that the addition of small amounts of sodium to a calcium clay results in a change in the clay particle bonding and orientation which alters the clay structure.
- v The amount of adsorbed calcium which is exchanged for sodium depends upon the concentration of the sodium leaching

solution. For a given soil-solution ratio, an increase in sodium adsorption occurs with an increase in the concentration of the sodium leaching solution.

vi A definite relationship exists between liquid limit and plasticity index for homionic modifications of the highly plastic Alberta clay tested. A straight line relationship between these values occurs which does not plot parallel to the A-line on the Casagrande plasticity chart.

vii The presence of carbonates in a soil tends to appreciably lower the cation exchange capacity.

8.3 Recommendations For Further Research

i It is recommended that an investigation be carried out to determine the effect of the adsorbed cation on the shear-strength of remoulded homionic clay samples.

ii A study similar to the present investigation should be undertaken to determine what effects other combinations of adsorbed cations might have on the physical or engineering properties of the clay.

iii As it has been shown by other workers that the concentration of cations in the pore solution has a marked effect on the physical properties of soil, it is suggested that a research programme be carried out using homionic soils and monoelectrolyte pore fluids, to determine the effects of pore fluid concentration on the physical properties of an Alberta clay.

iv At present, the practical applications of cation exchange are restricted mainly to the treatment of subgrade and embankment materials. Thus it is recommended that the effects of cation exchange on the compaction characteristics of clays be investigated. The use of the miniature Harvard compaction apparatus is recommended as this apparatus requires only small quantities of soil.

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APPENDIX A

TEST DATA SHEETS FOR NATURAL CLAY

UNIVERSITY of ALBERTA
 DEP'T of CIVIL ENGINEERING
 SOIL MECHANICS LABORATORY
 SPECIFIC GRAVITY

PROJECT THESIS
 SITE U. of A.
 SAMPLE
 LOCATION NATURAL CLAY
 HOLE DEPTH
 TECHNICIAN Hamilton DATE Nov. 1/60

Sample No.	1	2
Flask No.	101	101
Method of Air Removal	Vacuum	Vacuum
W_{b+w+s}	683.61	696.31
Temperature T	22.5 °C	21.2 °C.
W_{b+w}	667.24	667.42
Evaporating Dish No.	A1	A1
Wt. Sample Dry + Dish	154.70	178.41
Tare Dish	129.19	133.04
W_s	25.51	45.37
G_s	2.76	2.76

W_{b+w+s} = Weight of flask + water + sample at T° .

W_{b+w} = Weight of flask + water at T° (flask calibration curve).

W_s = Weight of dry soil

G_s = Specific gravity of soil particles =
$$\frac{W_s}{W_s + W_{b+w} - W_{b+w+s}}$$

Determination of W_s from wet soil sample:

Sample No.		Sample No.	
Container No.		Container No.	
Wt. Sample Wet + Tare		Wt. Test Sample Wet + Tare	
Wt. Sample Dry + Tare		Tare Container	
Wt. Water		Wt. Test Sample Wet	
Tare Container		W_s	
Wt. of Dry Soil			
Moisture Content $w\%$			

Description of Sample: Highly plastic dark brown clay - airdried.

Remarks: Average Specific Gravity, $G_s = 2.76$

UNIVERSITY of ALBERTA
DEPT. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
HYDROMETER TEST

PROJECT THESIS
SITE U of A
SAMPLE NATURAL CLAY
LOCATION Sample #1
HOLE DEPTH
TECHNICIAN HAMILTON DATE Dec 2/60

Date	Temp.	Time	Elapsed Time	R'_h	R_h $= R'_h + c_m$	D m.m.	$R_h + m_f - c_d$	W.%	W.% Basis Orig. Sample	Remarks
Dec. 2	22.4°C	3:30 pm	0							
	22.4		30 sec	1.0153	1.0158	0.070	1.0159	92.5		
	22.4		1 min	1.0150	1.0155	0.051	1.0156	90.7		
	22.4		2 min	1.0148	1.0153	0.036	1.0154	89.6		
	22.4	3:34 pm	4 min	1.0146	1.0151	0.023	1.0152	88.5		
	22.3	3:38 pm.	8 min	1.0145	1.0150	0.0180	1.0150	87.3		
	22.4	3:45 pm	15 min	1.0142	1.0147	0.0133	1.0149	86.6		
	22.4	4:00 pm	30 min	1.0138	1.0143	0.0092	1.0145	84.5		
	22.3	4:30 pm.	60 min	1.0130	1.0135	0.0069	1.0135	78.6		
	22.2	5:15 pm	105 min	1.0119	1.0124	0.0052	1.0125	72.7		
	21.5	7:20 pm	230 min	1.0100	1.0105	0.0036	1.0107	62.3		
	21.1	10:55 pm	445 min	1.0082	1.0087	0.00265	1.0085	49.5		
Dec. 3	21.1	11:32 a.m.	1202 min	1.0058	1.0063	0.00160	1.0061	35.6		
	21.1	9:10 pm.	1780 min	1.0047	1.0051	0.00132	1.0050	29.1		
Dec. 4	21.2	2:15 p.m.	2815 min	1.0039	1.0044	0.00108	1.0042	24.4		
Dec. 5	21.2	2:15 p.m.	4255 min	1.0030	1.0035	0.00086	1.0035	23.9		
Dec. 7	22.2	2:15 p.m.	7135 min	1.0026	1.0031	0.00065	1.0033	21.0		
Dec. 11	21.6	2:15 p.m.	12895 min	1.0021	1.0025	0.00036	1.0029	18.5		

Hydrometer No.s 9847 R and Graduate No. #1

$$W\% = \frac{100}{W_s} \cdot \frac{S_s}{S_s - 1} (R_h + m_f - c_d) = 5.82 (R_h + m_f - c_d)$$

Meniscus correction = $c_m = 0.0005$ and respectively

Dispersing agent used Calgon - 6% Amount 10 m.l.

Correction for change in density of liquid due to addition of dispersing agent = c_d

$c_d = 0.0004$ and respectively

Specific Gravity of Solids = G_s 2.76

Description of Sample

Dark, brown, highly plastic-clay.

Method of Preparation

Remarks

Initial Moisture Content

Container No. V 1
Wt. Sample Wet + Tare 112.0201
Wt. Sample Dry + Tare 110.8510
Wt. Water 1.16910
Tare Container 74.2648
Wt. of Dry Soil 36.5862
Initial Moisture w% 3.195%

Dry Weight of Sample

Container No. 34
Wt. Sample (Wet/Dry) + Tare
Tare
Wt. (Wet/Dry) Soil 27.7319
Dry Weight from Initial
Moisture = $\frac{100 \times \text{Wt. Wet Soil}}{100 + \text{Init. Moist. \%}} = 26.872 \text{ gms}$

UNIVERSITY of ALBERTA
DEP'T. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
HYDROMETER TEST

PROJECT THESIS
SITE U. of A
SAMPLE Natural Clay Sample #2
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE Dec 16/61.

Date	Temp.	Time	Elapsed Time	R'_h	R_h $= R'_h + c_m$	D m.m.	$R_h + m_f - c_d$	W. %	W. % Basis Orig. Sample	Remarks
Dec 2		3:40 pm	0							
			30 sec	1.0156	16.1	0.070	16.2	93.2		
			1 min	1.0156	16.1	0.051	16.2	93.2		
	22.5°C		2 min	1.0154	15.9	0.036	16.0	92.0		
	22.5°C	3:44	4 min	1.0153	15.8	0.025	15.9	91.4		
	22.5°C	3:48	8 min	1.0153	15.8	0.018	15.9	91.4		
	22.4°C	3:55	15 min.	1.0150	15.5	0.013	15.6	89.6		
	22.4°C	4:10	30 min	1.0148	15.3	0.0095	15.3	88.0		
	22.4°C	4:40	60 min	1.0139	14.4	0.0067	14.4	82.7		
	22.2°C	5:18	98 min	1.0127	13.2	0.0054	13.2	76.0		
	21.6°C	7:23	233 min	1.0107	11.2	0.0036	11.1	64.8		
	21.1°C	11:00 pm	440 min.	1.0089	9.4	0.0026	9.2	52.9		
Dec. 3	21.1°C	11:35 am	1195 min.	1.0061	6.6	0.00160	6.4	36.8		
	21.1°C	9:10 pm.	1770 min.	1.0052	5.7	0.00133	5.5	31.6		
Dec. 4	21.2°C	2:15 pm	2805 min.	1.0045	4.9	0.00108	4.6	26.4		

Hydrometer No.s 9847 R and #2 Graduate No.

$$W\% = \frac{100}{W_s} \cdot \frac{S_s}{S_s - 1} (R_h + m_f - c_d) = 5.75 (R_h + m_f - c_d)$$

Meniscus correction = c_m = 0.0005 and respectively

Dispersing agent used Calgon 6% Amount 10 ml.

Correction for change in density of liquid due to addition of dispersing agent = c_d

$$c_d = -0.0008 \text{ and } \text{respectively}$$

Specific Gravity of Solids = G_s 2.76

Description of Sample

Dark brown, highly plastic clay.

Method of Preparation

Remarks

Initial Moisture Content

Container No. V1

Wt. Sample Wet + Tare 112.0201

Wt. Sample Dry + Tare 110.8510

Wt. Water 1.1691

Tare Container 74.2648

Wt. of Dry Soil 36.5867

Initial Moisture w% 3.20%

Dry Weight of Sample

Container No. 28

Wt. Sample (Wet/Dry) + Tare

Tare

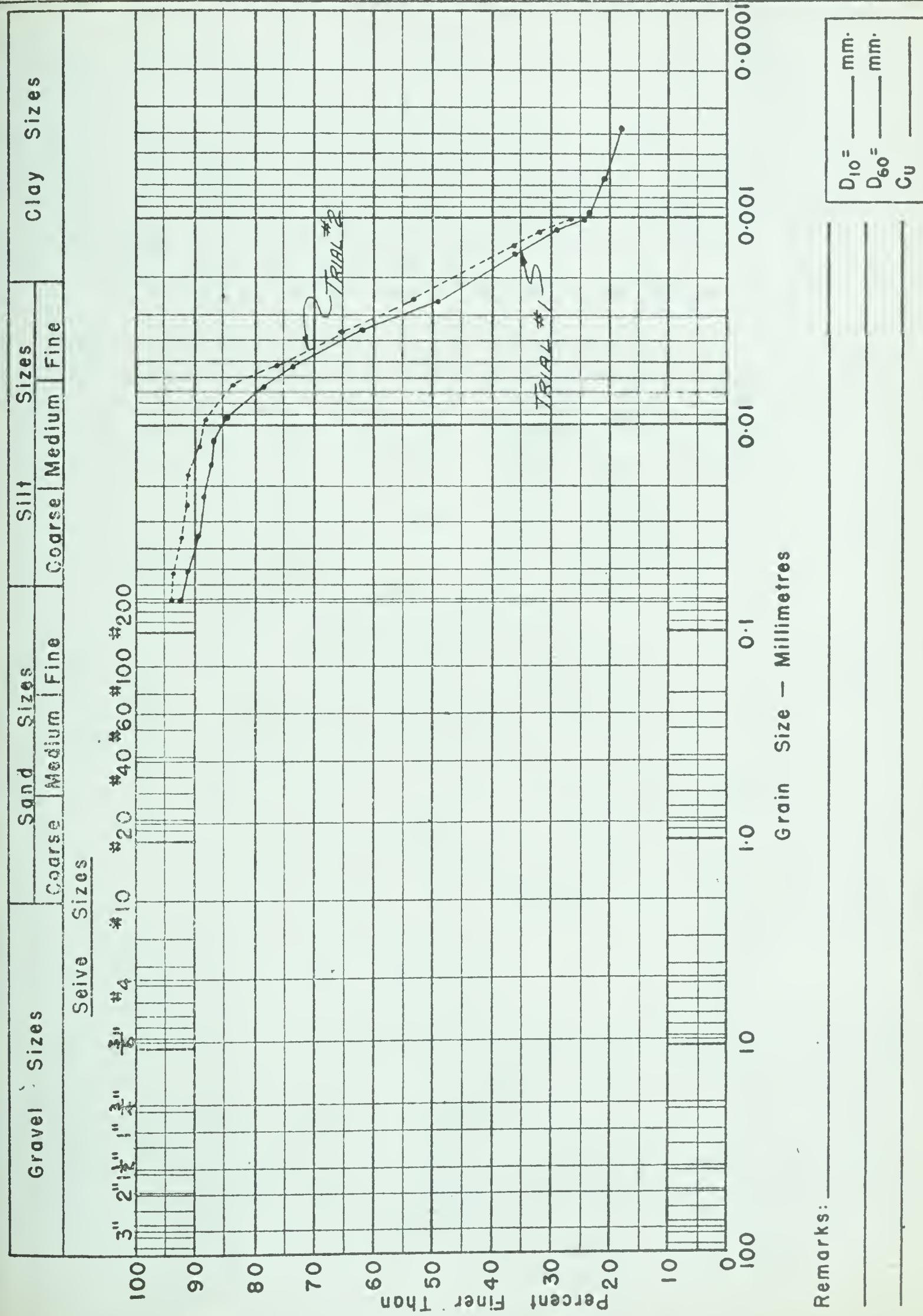
Wt. (Wet/Dry) Soil 28.1673

Dry Weight from Initial

$$\text{Moisture} = \frac{100 \times \text{Wt. Wet Soil}}{100 + \text{Init. Moist. \%}} = 27.293 \text{ gms.}$$

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SOIL MECHANICS LABORATORY
GRAIN SIZE CURVE

PROJECT THESIS
SITE U. of A.
SAMPLE Natural Clay.
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE Dec 12/60



Note: M.I.T. Grain Size Scale

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SOIL MECHANICS LABORATORY
ATTERBERG LIMITS

PROJECT THESIS
SITE U. of A.
SAMPLE NATURAL CLAY
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE Nov. 6/60

Liquid Limit

Trial No.	1	2	3	4	5
No. of Blows	28	24	20	18	16
Container No.	A 15	A 14	V 24	V 76	A 140
Wt. Sample Wet + Tare	83.081	85.036	97.110	80.433	78.750
Wt. Sample Dry + Tare	74.503	76.547	88.747	72.195	70.725
Wt. Water	8.578	8.489	8.363	8.238	8.025
Tare Container	63.115	65.489	77.878	61.619	60.614
Wt. of Dry Soil	11.388	11.058	10.869	10.576	10.111
Moisture Content w%	75.3	76.8	76.9	77.9	79.4

Average Values

$$w_l = 76.1$$

$$w_p = 28.9$$

$$w_s = 9.7$$

$$I_p = 47.2$$

$$I_f = \underline{\quad}$$

$$I_t = \underline{\quad}$$

Plastic Limit

Trial No.	1	2	3
Container No.	V 49	V 21	V 35
Wt. Sample Wet + Tare	69.607	75.570	79.368
Wt. Sample Dry + Tare	68.050	73.402	77.454
Wt. Water	1.557	2.168	1.914
Tare Container	62.788	65.848	70.752
Wt. of Dry Soil	5.262	7.554	6.702
Moisture Content %	29.6	28.7	28.6

Shrinkage Limit

Trial No.	1	2	3
Container No.	47	75	56
Wt. Sample Wet + Tare	131.97	139.80	120.42
Wt. Sample Dry + Tare	123.52	130.80	111.83
Wt. Water	8.45	9.00	8.55
Tare Container	113.96	120.65	102.20
Wt. of Dry Soil W _o	9.56	10.15	9.63
Moisture Content w%	88.39	88.67	88.78
Vol. Container V	12.90	13.50	13.10
Vol. Dry Soil Pat V _o	5.20	5.70	5.45
Shrinkage Vol. V-V _o	7.70	7.80	7.65
Shrinkage Limit w _s	7.9	11.82	9.3

$$w_s = w_r \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample: Highly plastic dark brown clay - air. dried.

Remarks:

7 8 9 10 15 20 25 30 40
Number of Blows

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CONSOLIDATION RESULTS

PROJECT THESIS
SITE U. of A.
SAMPLE NATURAL CLAY TRIAL #1
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE Nov. 7/60

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.3050$ ins.

Void Ratio e (End) = 1.0800

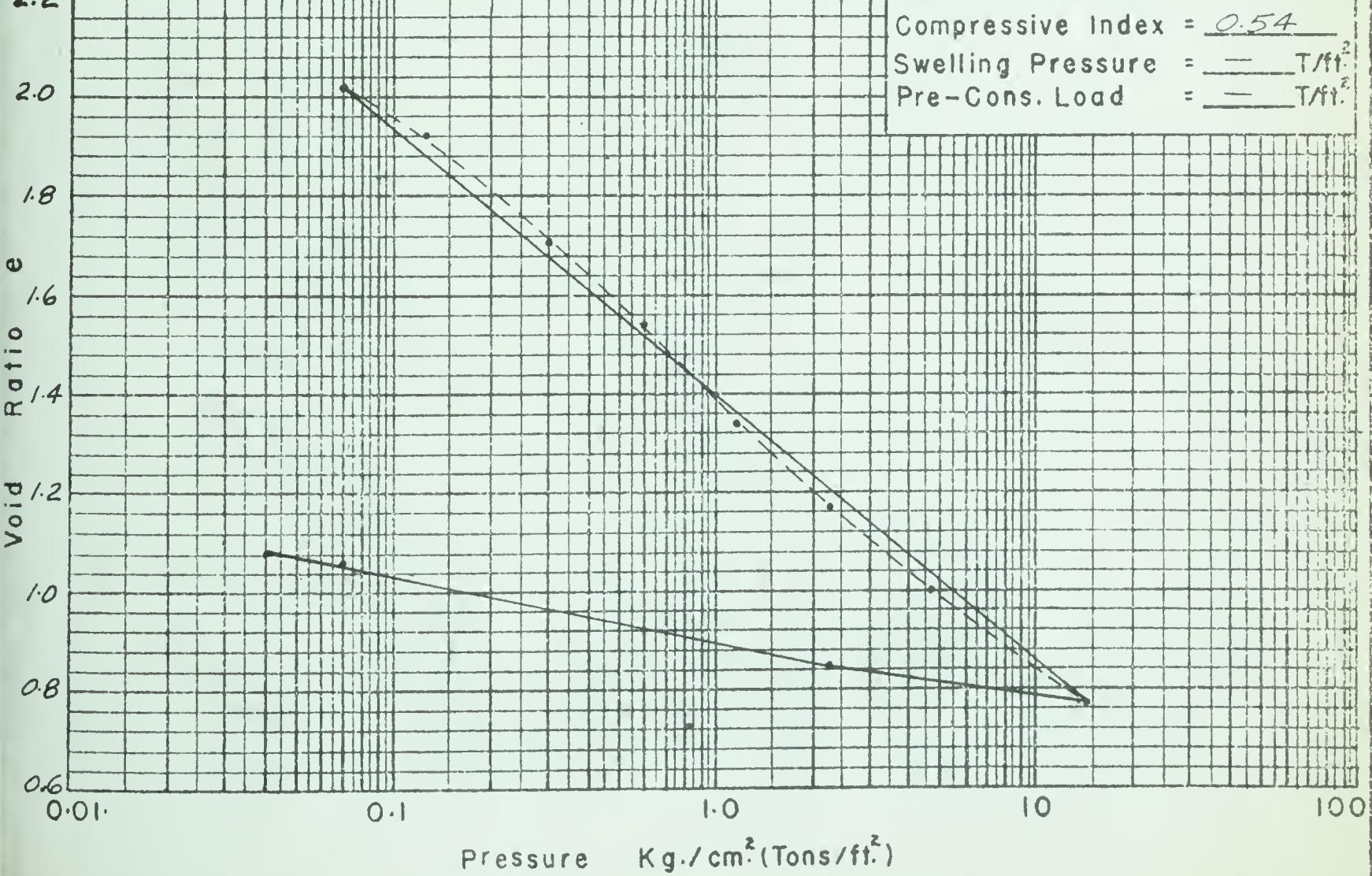
Void Ratio e (Start) = 2.2314

Void Ratio e (Start Dimensions) =

$$e(\text{End}) = W\%(\text{End}) \times G_s \quad H_s = \left(\frac{W \cdot \text{Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.} \quad e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = \text{T/ft}^2$
	0	0.7000	0	0	2.2314	0
1 Day	20	0.6345	0.0655	0.2148	2.0166	0.07
✓	40	0.6059	0.0286	0.0938	1.9228	0.13
✓	100	0.5408	0.0651	0.2134	1.7094	0.30
✓	200	0.4905	0.0503	0.1649	1.5445	0.60
✓	400	0.4287	0.0618	0.2024	1.3421	1.18
✓	800	0.3767	0.0520	0.1705	1.1716	2.35
✓	1600	0.3251	0.0516	0.1692	1.0024	4.69
✓	5000	0.2544	0.0707	0.2320	0.7704	14.67
✓	800	0.2781	0.0237	0.0778	0.8428	2.35
✓	20	0.3421	0.0640	0.2098	1.0580	0.07
✓	10	0.3488	0.0067	0.0220	1.0800	0.04

2.2



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SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	NATURAL CLAY TRIAL #2
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAMILTON DATE Nov. 11/61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.3170$ ins.

Void Ratio e (End) = 1.1800

Void Ratio e (Start) = 2.2921

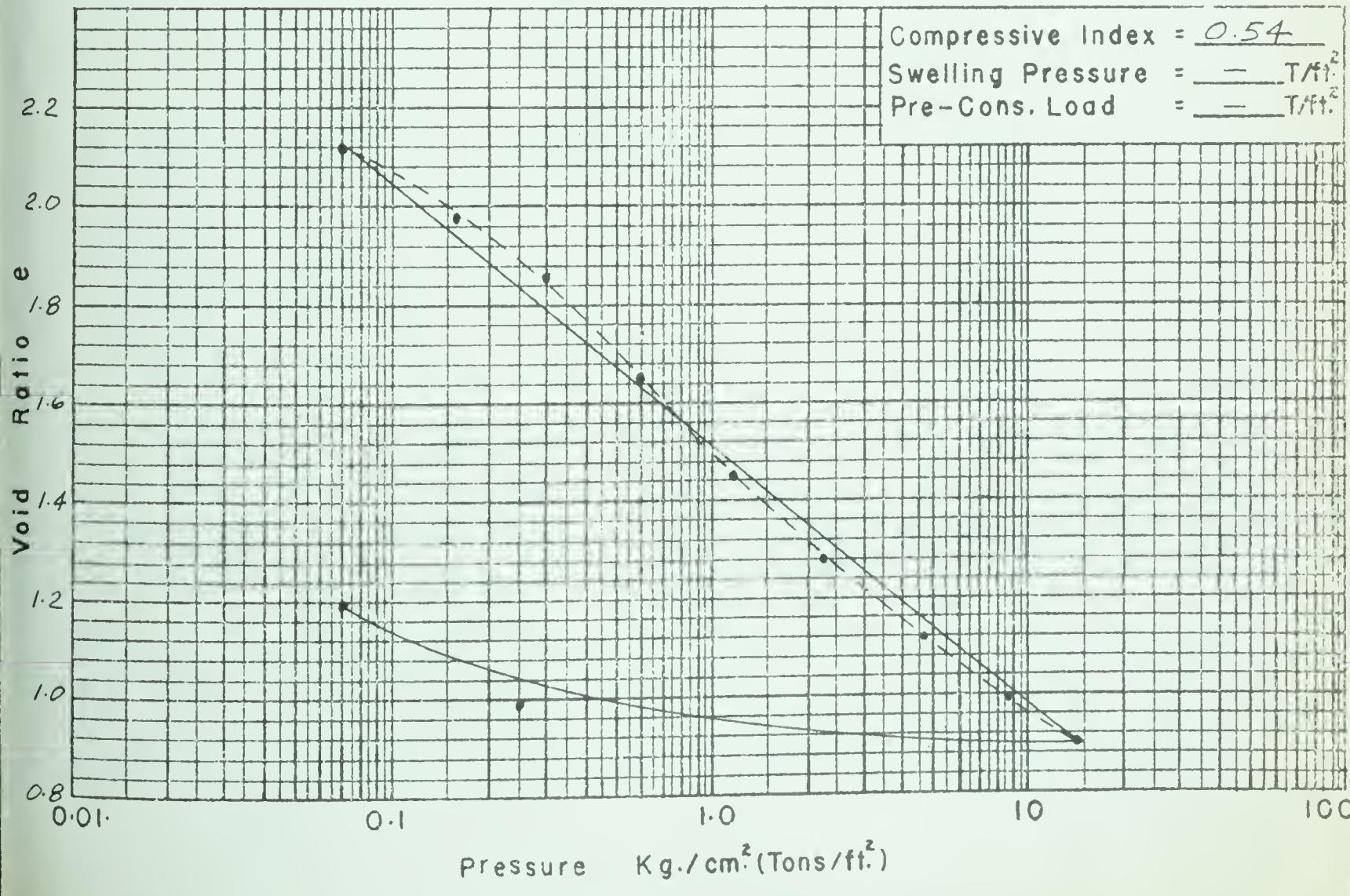
Void Ratio e (Start Dimensions) =

e (End) = $W\% \text{ (End)} \times G_s$

$$H_s = \left(\frac{W \cdot \text{Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.}$$

$$e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = \text{T/ft}^2$
	0	0.4000	0	0	2.2921	0
1 Day	20	0.3449	0.0551	0.1705	2.1216	0.07
✓	50	0.2990	0.0459	0.1445	1.9771	0.16
✓	100	0.2608	0.0382	0.1205	1.8566	0.30
✓	200	0.1964	0.0644	0.2030	1.6536	0.60
✓	400	0.1345	0.0619	0.1950	1.4586	1.18
✓	800	0.0790	0.0555	0.1750	1.2836	2.35
✓	1600	0.0290	0.0500	0.1575	1.1261	4.69
✓	3000	0.9870	0.0420	0.1325	0.9936	8.83
✓	5000	0.9572	0.0278	0.0877	0.9059	14.67
✓	800	0.9849	0.0257	0.0811	0.9870	0.25
✓	20	1.0461	0.0612	0.1930	1.1800	0.07



NATURAL CLAY
DIAL READING - TIME CURVE
0.60 - 1.18 kg./cm² INCREMENT
TRAIL No. 2

DIAL READING (INCHES)

10,000
1000
100
10
1.0
0.0

TIME (MINUTES)



APPENDIX B

TEST DATA SHEETS FOR HOMIONIC CLAYS

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 ATTERBERG LIMITS

PROJECT THESIS
 SITE U of A.
 SAMPLE Potassium Clay (K^+ -clay)
 LOCATION
 HOLE DEPTH
 TECHNICIAN HAMILTON DATE 24 Jan 61

Liquid Limit

Trial No.	1	2	3	4	5	6
No. of Blows	32	32	34	22	19	19
Container No.	V 3	V 23	V 39	V 40	V 60	V 4
Wt. Sample Wet + Tare	74.996	82.040	74.963	69.931	71.802	72.754
Wt. Sample Dry + Tare	71.558	77.615	70.868	65.088	66.464	68.893
Wt. Water	3.438	4.425	4.095	4.843	5.338	3.861
Tare Container	66.504	71.093	64.802	58.229	58.964	63.446
Wt. of Dry Soil	5.054	6.522	6.066	6.859	7.500	5.447
Moisture Content w%	68.02	67.84	67.50	70.61	71.17	70.88

Average Values

$$w_l = 69.5$$

$$w_p = 32.6$$

$$w_s = 17.2$$

$$I_p = 36.9$$

$$I_f = \text{---}$$

$$I_t = \text{---}$$

Plastic Limit

Trial No.	1	2	3
Container No.	V 4	V 3	V 23
Wt. Sample Wet + Tare	69.339	72.656	77.680
Wt. Sample Dry + Tare	67.847	71.144	76.063
Wt. Water	1.492	1.512	1.617
Tare Container	63.446	66.504	71.093
Wt. of Dry Soil	4.401	4.640	4.970
Moisture Content %	33.90	32.58	32.53

Shrinkage Limit

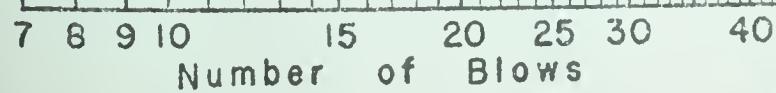
Trial No.	1	2	3
Container No.	156	13	80
Wt. Sample Wet + Tare	121.14	131.20	141.09
Wt. Sample Dry + Tare	113.04	122.39	132.78
Wt. Water	8.10	8.81	8.31
Tare Container	102.08	110.25	121.57
Wt. of Dry Soil W_o	10.96	12.14	11.21
Moisture Content w%	73.91	72.57	74.13
Vol. Container V	12.6	13.6	12.9
Vol. Dry Soil Pat V_o	6.3	7.0	6.5
Shrinkage Vol. $V - V_o$	6.3	6.6	6.4
Shrinkage Limit w_s	16.4	18.2	17.04

$$w_s = w \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample:

Homionic K^+ -Clay

Remarks:



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ATTERBERG LIMITS

PROJECT THESIS
SITE U of A.
SAMPLE Sodium Clay (Na^+ -clay)
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 23 Jan/61

Liquid Limit

Trial No.	1	2	3	4	5	6
No. of Blows	28	28	30	19	15	16
Container No.	V4	V3	V23	V39	V40	V60
Wt. Sample Wet + Tare	71.3280	75.369	80.646	77.274	69.647	69.960
Wt. Sample Dry + Tare	67.481	71.048	75.995	71.118	64.018	64.541
Wt. Water	3.847	4.321	4.651	6.156	5.629	58.564
Tare Container	63.446	66.504	71.093	64.802	58.229	5.577
Wt. of Dry Soil	4.035	4.544	4.902	6.316	5.789	97.16
Moisture Content $w\%$	95.34	95.09	94.87	97.46	97.23	

Average Values

$$w_l = 95.7$$

$$w_p = 26.4$$

$$w_s = 13.8$$

$$I_p = 69.3$$

$$I_f = \underline{\quad}$$

$$I_t = \underline{\quad}$$

Plastic Limit

Trial No.	1	2	3
Container No.	V39	V40	V60
Wt. Sample Wet + Tare	68.575	64.759	64.303
Wt. Sample Dry + Tare	67.788	63.332	63.187
Wt. Water	0.787	1.427	1.116
Tare Container	64.802	58.229	58.964
Wt. of Dry Soil	2.986	5.103	4.223
Moisture Content %	26.35	27.96	26.42

Shrinkage Limit

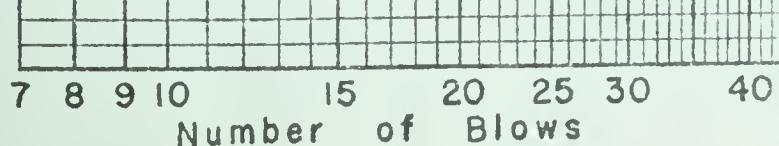
Trial No.	1	2	3
Container No.	73	93	75
Wt. Sample Wet + Tare	130.15	141.34	138.93
Wt. Sample Dry + Tare	121.20	132.40	129.55
Wt. Water	8.85	8.90	9.38
Tare Container	112.58	124.78	120.62
Wt. of Dry Soil W _o	8.62	7.62	8.93
Moisture Content $w\%$	102.67	116.79	105.03
Vol. Container V	12.60	12.10	13.20
Vol. Dry Soil Pat V _o	4.70	4.40	5.00
Shrinkage Vol. V-V _o	7.90	7.70	8.20
Shrinkage Limit w_s	11.03	16.50	13.21

$$w_s = w \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample: _____

Homogenic Na^+ -Clay.

Remarks: _____



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ATTERBERG LIMITS

PROJECT THESIS
SITE 11 of A
SAMPLE CALCIUM CLAY (Ca^{++} Clay)
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 23 Jan 61

Liquid Limit

Trial No.	1	2	3	4	5	6
No. of Blows	35	31	34	20	21	22
Container No.	V51	V54	V34	V58	V26	A12
Wt. Sample Wet + Tare	67.658	68.722	75.246	76.298	73.577	80.195
Wt. Sample Dry + Tare	63.971	65.041	70.515	72.090	69.708	74.560
Wt. Water	3.687	3.681	4.731	4.208	3.869	5.635
Tare Container	59.239	60.299	64.387	66.936	64.923	67.545
Wt. of Dry Soil	4.732	4.742	6.128	5.154	4.785	7.015
Moisture Content w%	77.92	77.62	77.20	81.64	80.85	80.33

Average Values

$$w_l = \frac{79.7}{6}$$

$$w_p = \frac{31.0}{6}$$

$$w_s = \frac{12.3}{6}$$

$$I_p = \frac{48.7}{6}$$

$$I_f = \frac{20.3}{6}$$

$$I_t = \frac{20.3}{6}$$

Plastic Limit

Trial No.	1	2	3
Container No.	V26	A12	V51
Wt. Sample Wet + Tare	70.315	72.301	63.633
Wt. Sample Dry + Tare	69.075	71.176	62.595
Wt. Water	1.240	1.125	1.038
Tare Container	64.923	67.545	59.239
Wt. of Dry Soil	4.152	3.631	3.356
Moisture Content %	29.86	30.98	30.93

Shrinkage Limit

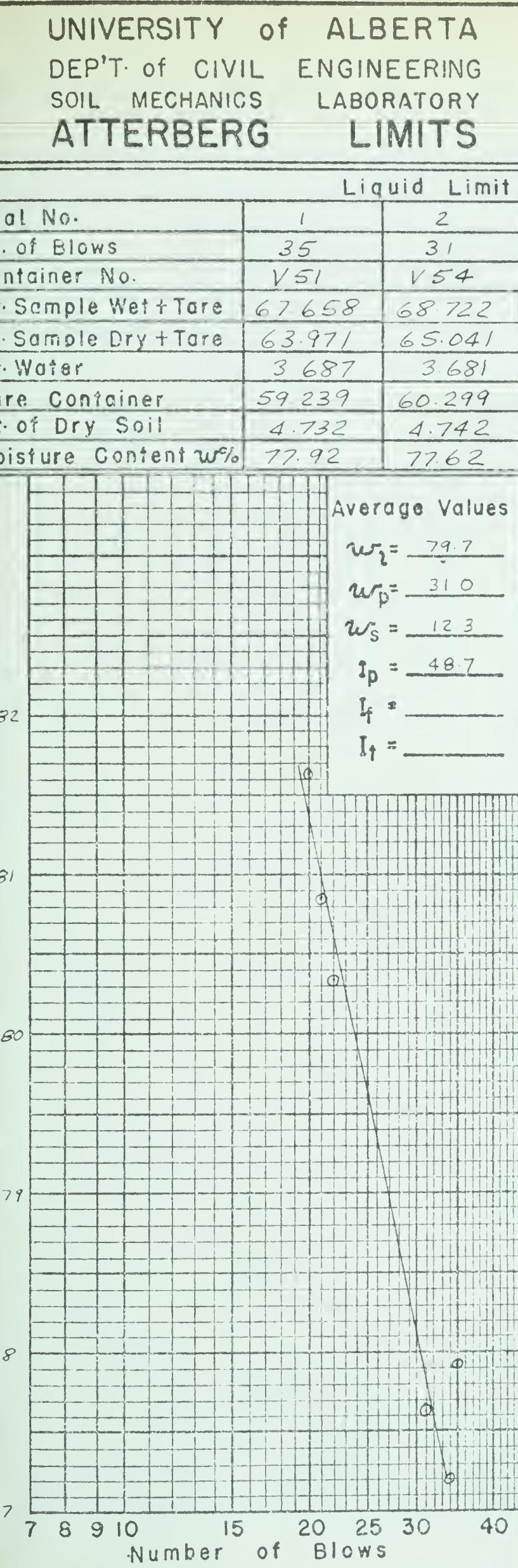
Trial No.	1	2	3
Container No.	81	76	67
Wt. Sample Wet + Tare	118.64	135.78	126.47
Wt. Sample Dry + Tare	109.65	127.40	118.11
Wt. Water	8.99	8.38	8.36
Tare Container	99.21	117.86	108.62
Wt. of Dry Soil W _o	10.44	9.54	9.49
Moisture Content w% _s	86.11	87.84	88.09
Vol. Container V	12.70	12.40	12.40
Vol. Dry Soil Pat V _o	5.40	5.20	5.20
Shrinkage Vol. V-V _o	7.30	7.20	7.20
Shrinkage Limit w _s	(16.19)	12.37	12.22

$$w_s = w_p \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample:

Homionic Ca^{++} Clay.

Remarks:



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SOIL MECHANICS LABORATORY
ATTERBERG LIMITS

PROJECT THESIS
SITE U of A.
SAMPLE Magnesium Clay ($Mg^{++}Clay$).
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 24 Jan 61

Liquid Limit

Trial No.	1	2	3	4	5	6
No. of Blows	30	35	34	18	20	19
Container No.	A12	V58	V34	V54	V26	V51
Wt. Sample Wet + Tare	78.913	76.910	73.860	70.609	76.621	69.817
Wt. Sample Dry + Tare	73.982	72.594	69.739	65.976	71.366	65.071
Wt. Water	4.931	4.316	4.121	4.633	5.255	4.746
Tare Container	67.545	66.936	64.387	60.299	64.923	59.239
Wt. of Dry Soil	6.437	5.658	5.352	5.677	6.443	5.832
Moisture Content $w\%$	77.60	76.28	77.00	81.61	81.58	81.55

Average Values

$$w_l = 79.2$$

$$w_p = 30.1$$

$$w_s = 14.3$$

$$I_p = 49.1$$

$$I_f = \underline{\quad}$$

$$I_t = \underline{\quad}$$

Plastic Limit

Trial No.	1	2	3
Container No.	V34	V54	V58
Wt. Sample Wet + Tare	69.746	68.072	76.532
Wt. Sample Dry + Tare	68.511	66.285	74.296
Wt. Water	1.235	1.787	2.236
Tare Container	64.387	60.299	66.936
Wt. of Dry Soil	4.124	5.986	7.360
Moisture Content %	29.94	29.85	30.38

Shrinkage Limit

Trial No.	1	2	3
Container No.	90	97	47
Wt. Sample Wet + Tare	140.56	140.25	132.01
Wt. Sample Dry + Tare	132.04	131.79	123.41
Wt. Water	8.52	8.46	8.60
Tare Container	122.64	122.28	113.91
Wt. of Dry Soil W_o	9.40	9.51	9.50
Moisture Content $w\%$	90.64	88.96	90.52
Vol. Container V	13.40	12.30	12.50
Vol. Dry Soil Pat V_o	5.15	5.15	5.30
Shrinkage Vol. $V - V_o$	8.25	7.15	7.20
Shrinkage Limit w_s	(2.88)	13.78	14.74

$$w_s = w \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample: _____

Homionic $Mg^{++}Clay$

Remarks: _____

7 8 9 10 15 20 25 30 40
Number of Blows

Moisture Content %

82

81

80

79

78

77

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 SOIL MECHANICS LABORATORY
 CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	Hemianic K ⁺ Clay.
LOCATION	
HOLE	DEPTH
TECHNICIAN HAMILTON	DATE 14 Feb. 61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2475$ ins.

Void Ratio e (End) = 1.5120

Void Ratio e (Start) = 2.2172

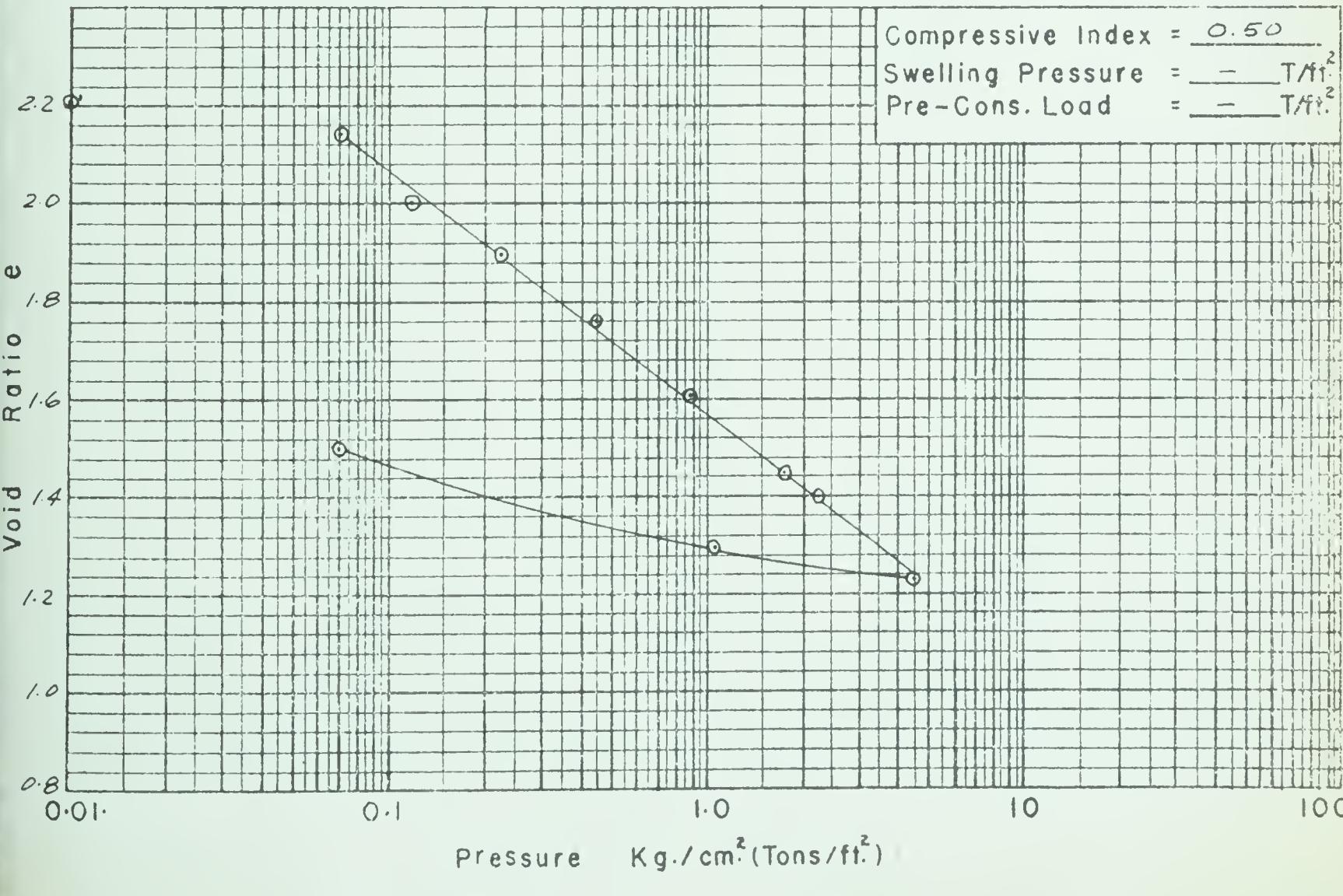
Void Ratio e (Start Dimensions) =

e (End) = $W\%(\text{End}) \times G_s$

$$H_s = \left(\frac{W \cdot \text{Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.}$$

$$e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = \text{T/ft}^2$
	0	0.8000	0	0	2.2172	0
2 Days	50	0.7800	0.0200	0.0809	2.1363	0.07
2 Days	100	0.7458	0.0342	0.1382	1.9981	0.12
1 Day	200	0.7216	0.0242	0.0978	1.9003	0.23
1 Day	400	0.6881	0.0335	0.1355	1.7648	0.45
1 Day	800	0.6508	0.0373	0.1508	1.6141	0.89
1 Day	1600	0.6094	0.0414	0.1674	1.4467	1.77
2 Days	2080	0.5972	0.0122	0.0494	1.3973	2.29
2 Days	4160	0.5551	0.0421	0.1702	1.2271	4.56
1 Day	1000	0.5716	0.0165	0.0667	1.2938	1.11
3 Days	50	0.6256	0.0540	0.2182	1.5120	0.07

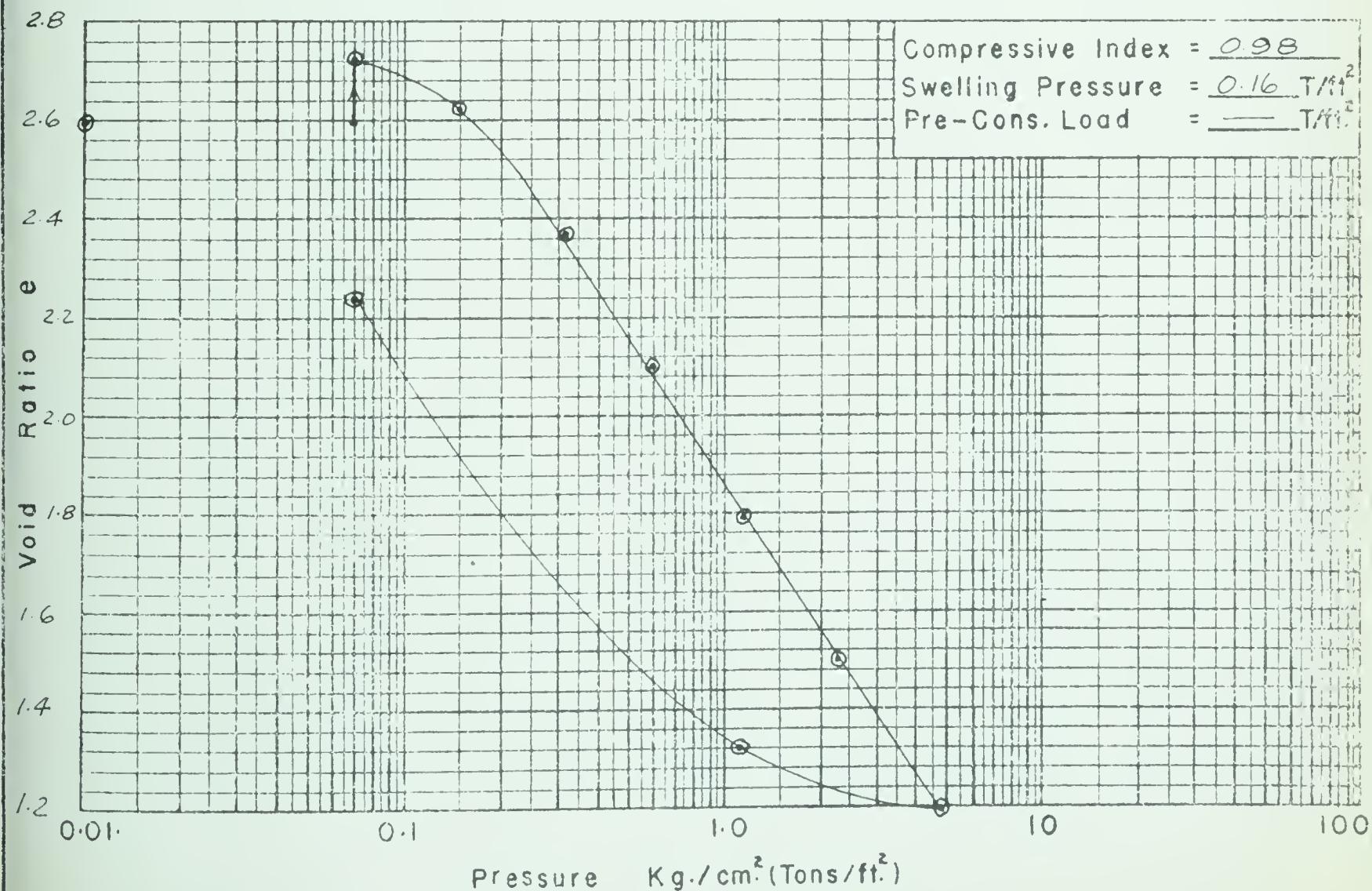


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SOIL MECHANICS LABORATORY
CONSOLIDATION RESULTS

PROJECT THESIS
SITE U. of A
SAMPLE Homionic Na^+ Clay
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 15 Mar 61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2399$ ins.
 Void Ratio e (End) = 2.2420
 Void Ratio e (Start) = 2.5968
 Void Ratio e (Start Dimensions) =
 $e(\text{End}) = W\%(\text{End}) \times G_s$ $H_s = \left(\frac{W\% \text{ Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.}$ $e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = T/\text{ft}^2$
	0	0.7000	0	0	2.5968	0
5 Days	20	0.7300	0.0300	0.1251	2.7219	0.07
5 Days	50	0.7055	0.0245	0.1022	2.6197	0.15
4 Days	100	0.6459	0.0596	0.2485	2.3712	0.31
4 Days	200	0.5800	0.0659	0.2750	2.0962	0.60
4 Days	400	0.5015	0.0725	0.3022	1.7940	1.18
4 Days	800	0.4367	0.0708	0.2952	1.4988	2.36
6 Days	1600	0.3632	0.0735	0.3065	1.1923	4.70
10 Days	400	0.3943	0.0311	0.1297	1.3220	1.18
7 Days	20	0.6146	0.2203	0.9200	2.2420	0.07



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CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	HOMIONIC Ca^{++} CLAY
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAMILTON DATE 2 Mar. 61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.322$ ins.

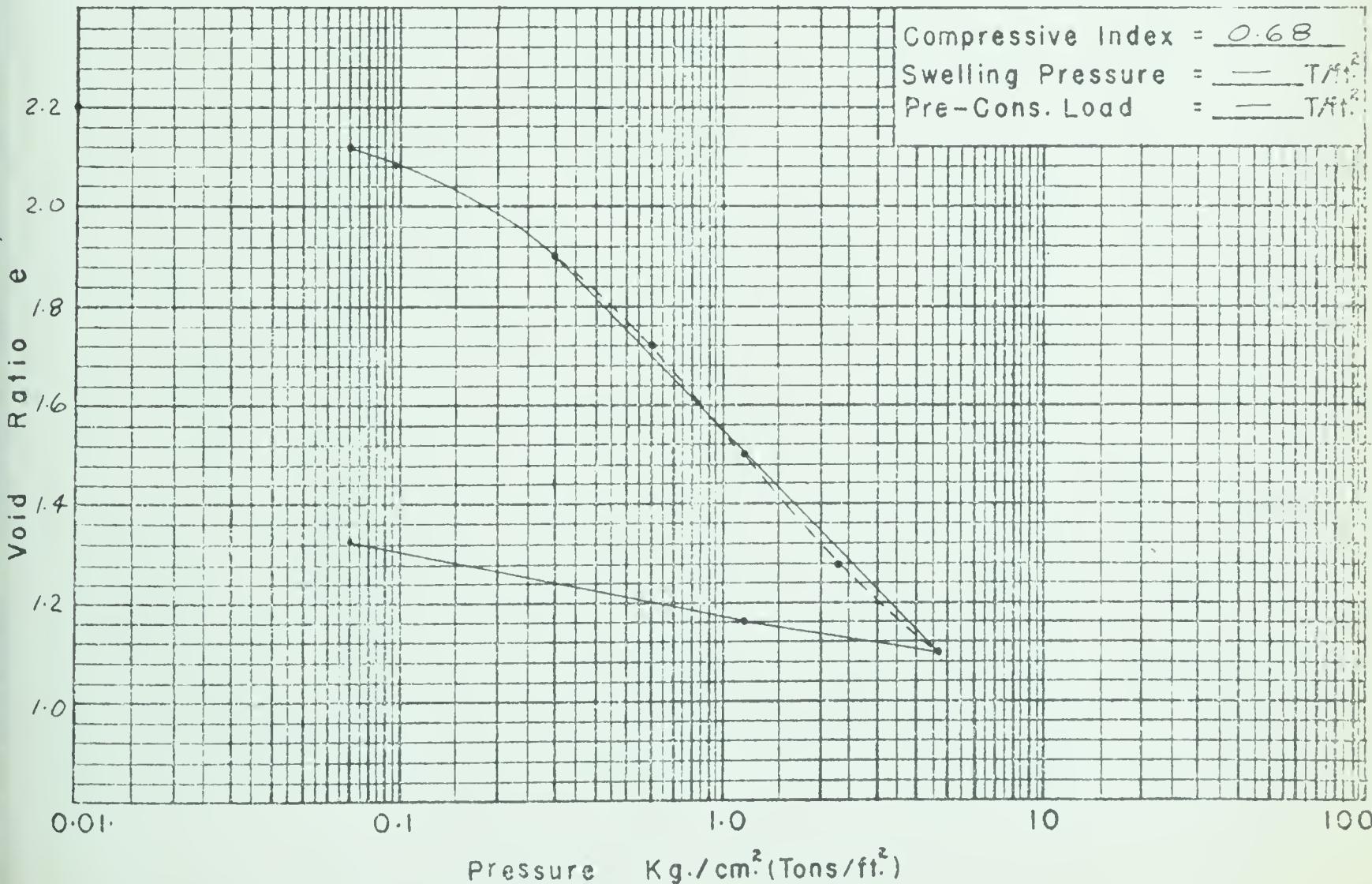
Void Ratio e (End) = 1.3260

Void Ratio $e(\text{Start}) =$ 2.2003

Void Ratio e (Start Dimensions) =

$$e(\text{End}) = W\%(\text{End}) \times G_s \quad H_s = \left(\frac{Wt \cdot \text{Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.} \quad e = \text{previous } e \pm \frac{\text{Def'l.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = T/\text{ft}^2$
	0	0.9000	0	0	2.2003	0
1 Day	20	0.8741	0.0259	0.0804	2.1199	0.07
1 Days	100	0.8032	0.0709	0.2179	1.9020	0.30
2 Days	200	0.7439	0.0593	0.1840	1.7181	0.60
2 Days	400	0.6692	0.0747	0.2310	1.4870	1.18
2 Days	800	0.6028	0.0664	0.2060	1.2810	2.35
1 Day	1600	0.5444	0.0584	0.1811	1.0999	4.69
3 Days	400	0.5634	0.0190	0.0590	1.1589	1.18
3 Days	20	0.6172	0.0538	0.1671	1.3260	0.07



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CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	Homionic Mg^{++} Clay.
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAMILTON
	DATE 3 Mar 61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.3018$ ins.

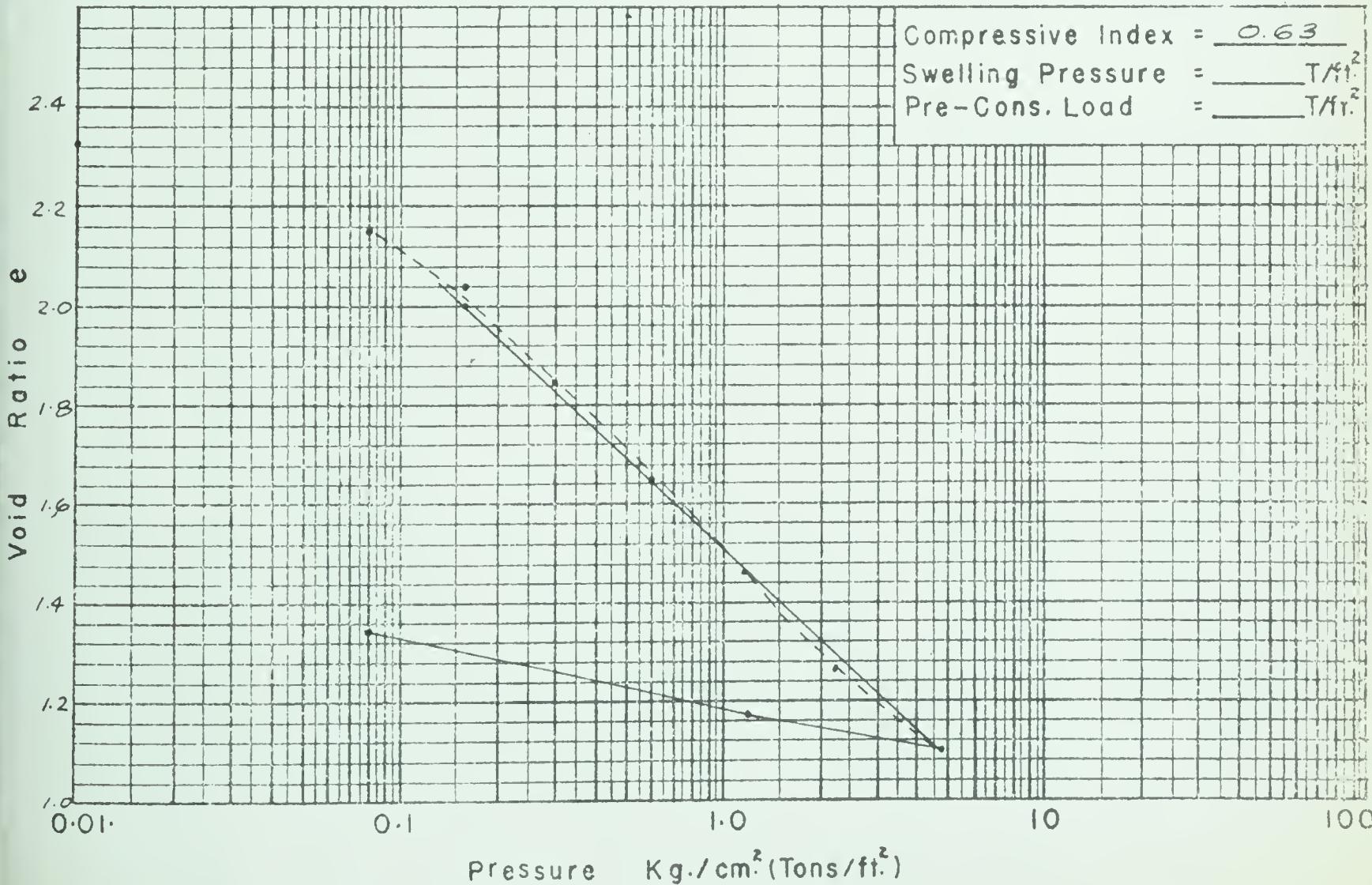
Void Ratio e (End) = 1.3415

Void Ratio $e(\text{Start}) = 2.3269$

Void Ratio e (Start Dimensions) = _____

$$e(\text{End}) = W\%(\text{End}) \times G_s \quad H_s = \left(\frac{Wt \cdot \text{Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.} \quad e = \text{previous } e \pm \frac{\text{Def'l.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = T/\text{ft}^2$
	0	0.9590	0	0	2.3269	0
2 Days	50	0.9050	0.0540	0.1790	2.1479	0.08
3 Days	100	0.8751	0.0299	0.0992	2.0487	0.16
2 Days	200	0.8160	0.0591	0.1960	1.8517	0.30
2 Days	400	0.7565	0.0595	0.1974	1.6545	0.60
1 Day	800	0.6970	0.0595	0.1974	1.4570	1.18
1 Day	1600	0.6419	0.0551	0.1826	1.2744	2.35
1 Day	3200	0.5899	0.0520	0.1724	1.1020	4.70
1 Day	800	0.6100	0.0201	0.0665	1.1685	1.18
2 Days	50	0.6622	0.0522	0.1730	1.3415	0.08



HOMONIC K-CLAY
DIAL READING-TIME CURVE
 $0.45 + 0.89 \text{ kg/cm}^2/\text{INCLEMENT}$

DIAL READING (INCHES)

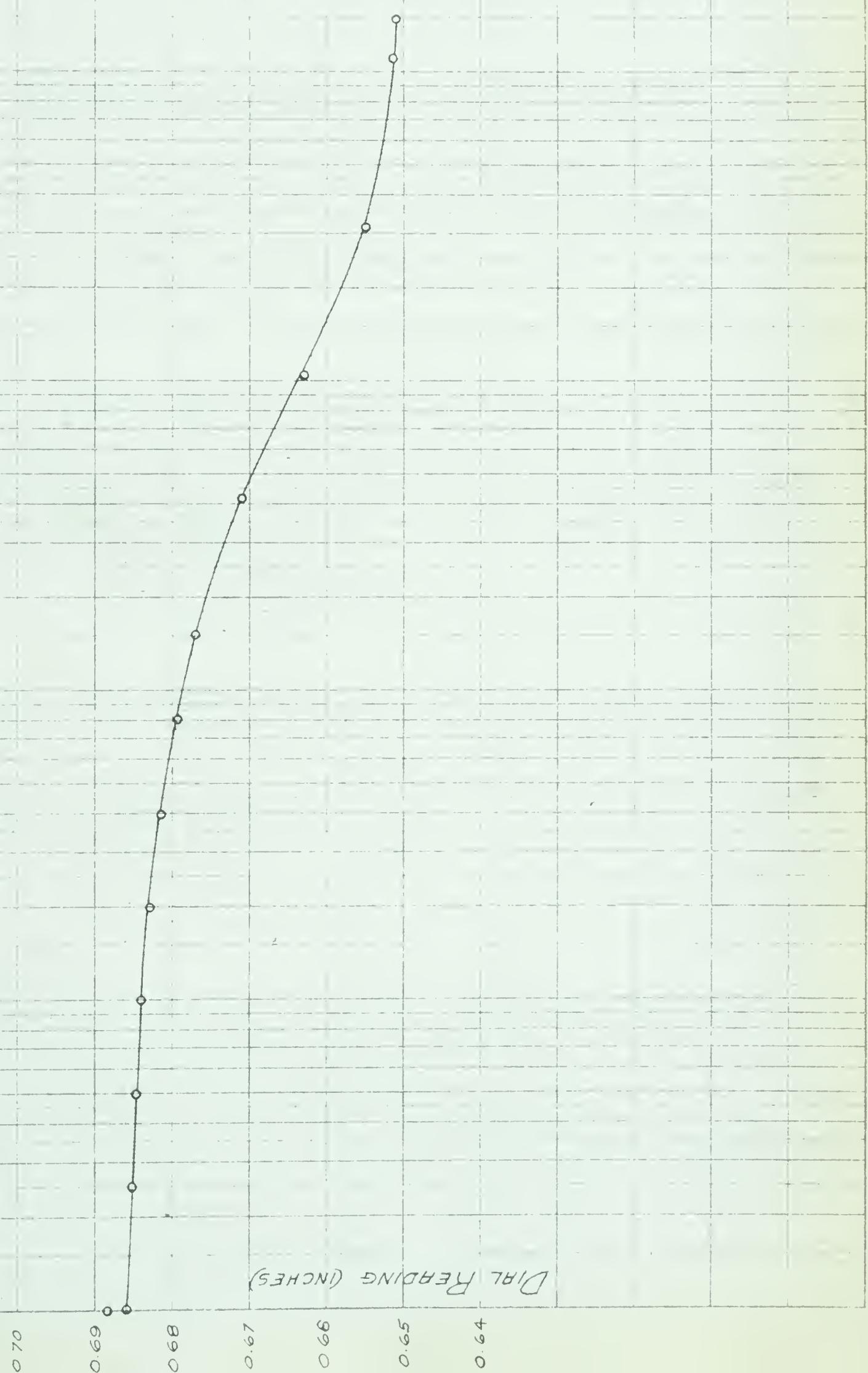
0.1

1.0

10 TIME (MINUTES)

1000

10,000



HOMONIC K-CLAY
DIAL READING - TIME CURVE
0.89 - 1.77 kg/cm² INCREMENT

DIAL READING (INCHES)

10,000

1000

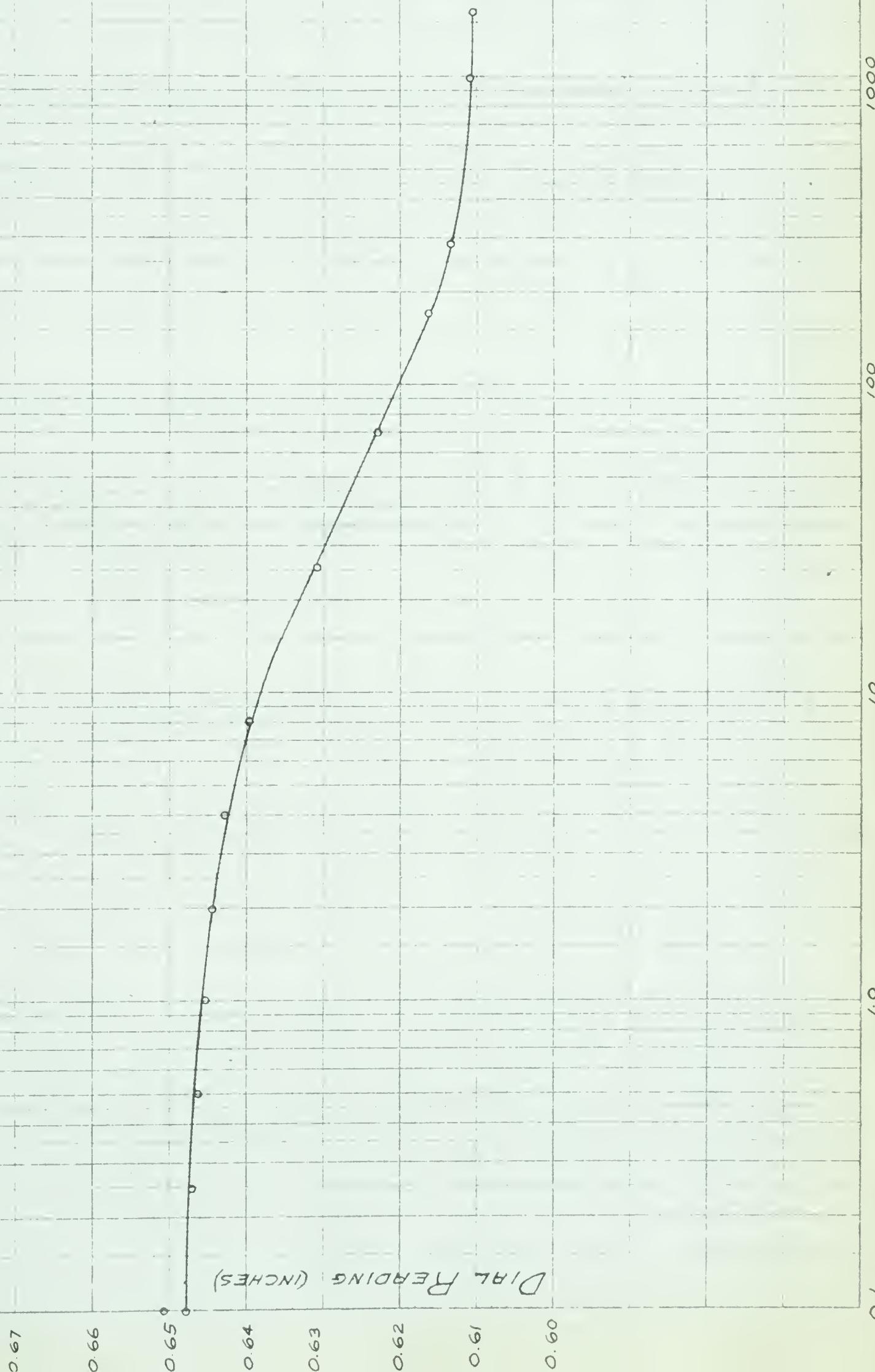
100

10

1.0

0.1

TIME (MINUTES)



HOMONIC Na-CLAY
DIAL READING - TIME CURVE
0 - 0.07 kg/cm² INCREMENT

DIAL READING (INCHES)

0.73

0.72

0.71

0.70

0.69

0.68

0.1

1.0

100

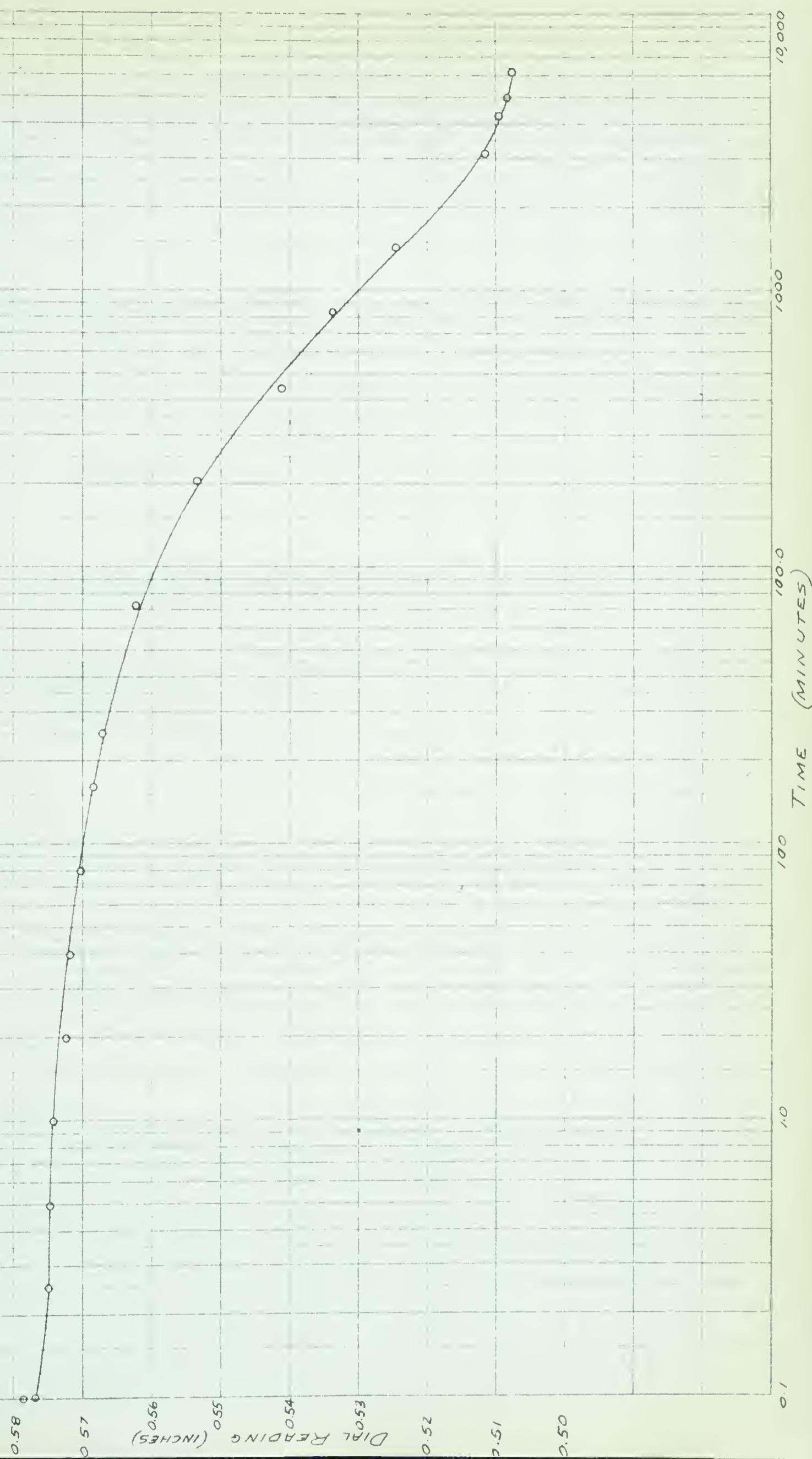
TIME (MINUTES)

1000

10,000

water added to cover sample

HOM/ONC Na-CLAY
DIAL READING - TIME CURVE
0.60 - 1/18 kg/cm² INCREMENT



HOMONIC Ca - CLAY
DIAL READING - TIME CURVE

0.60-1.18

kg./cm² INCREMENT

DIAL READING (INCHES)

TIME (MINUTES)

10000

1000

100

10

1.0

0.1

0.75

0.74

0.73

0.72

0.71

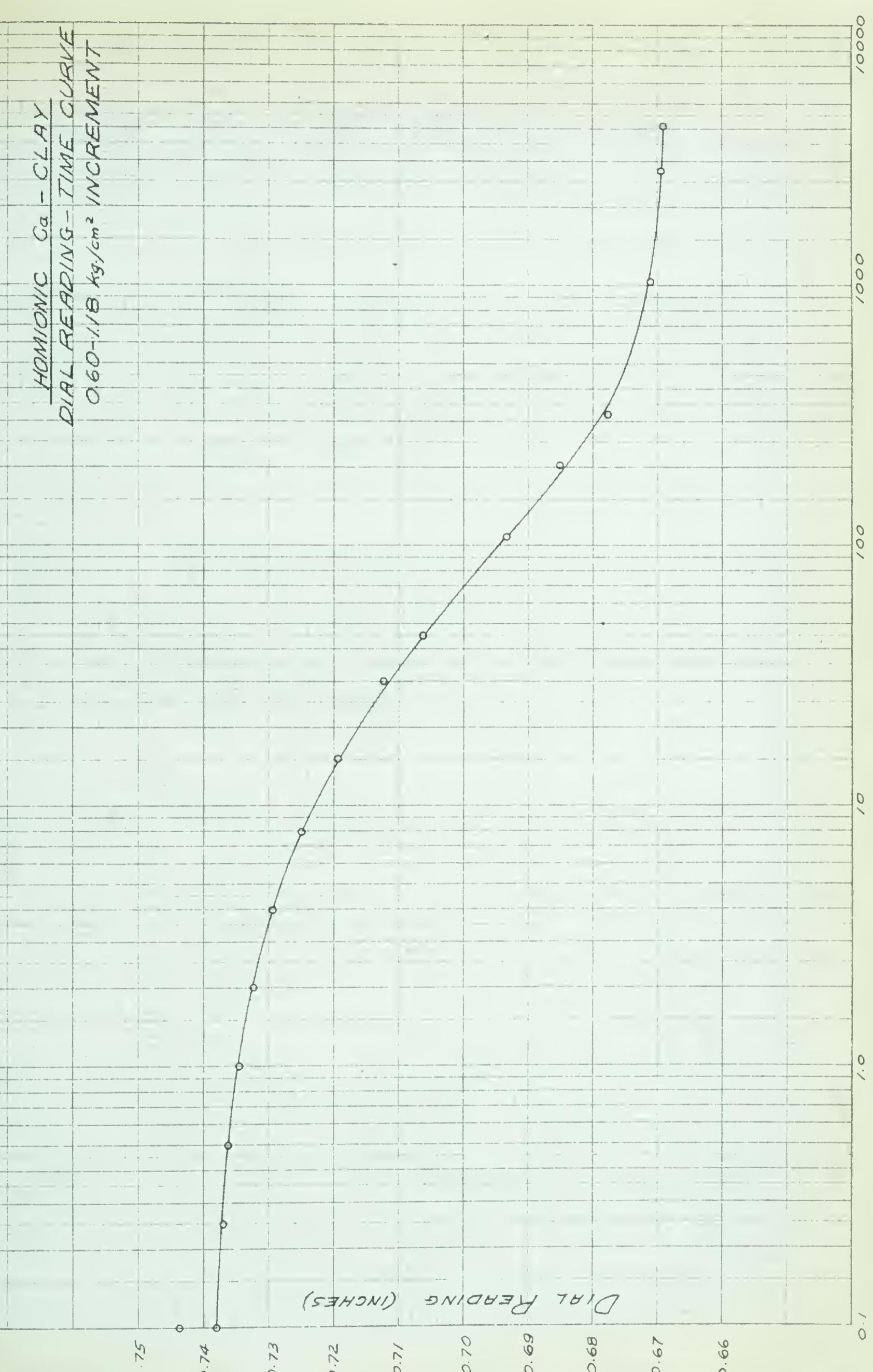
0.70

0.69

0.68

0.67

0.66



HOMIONIC Mg - CLAY
DIAL READING - TIME CURVE
0.60 - 1/8 Kg/cm² INCREMENT

DIAL READING (INCHES)

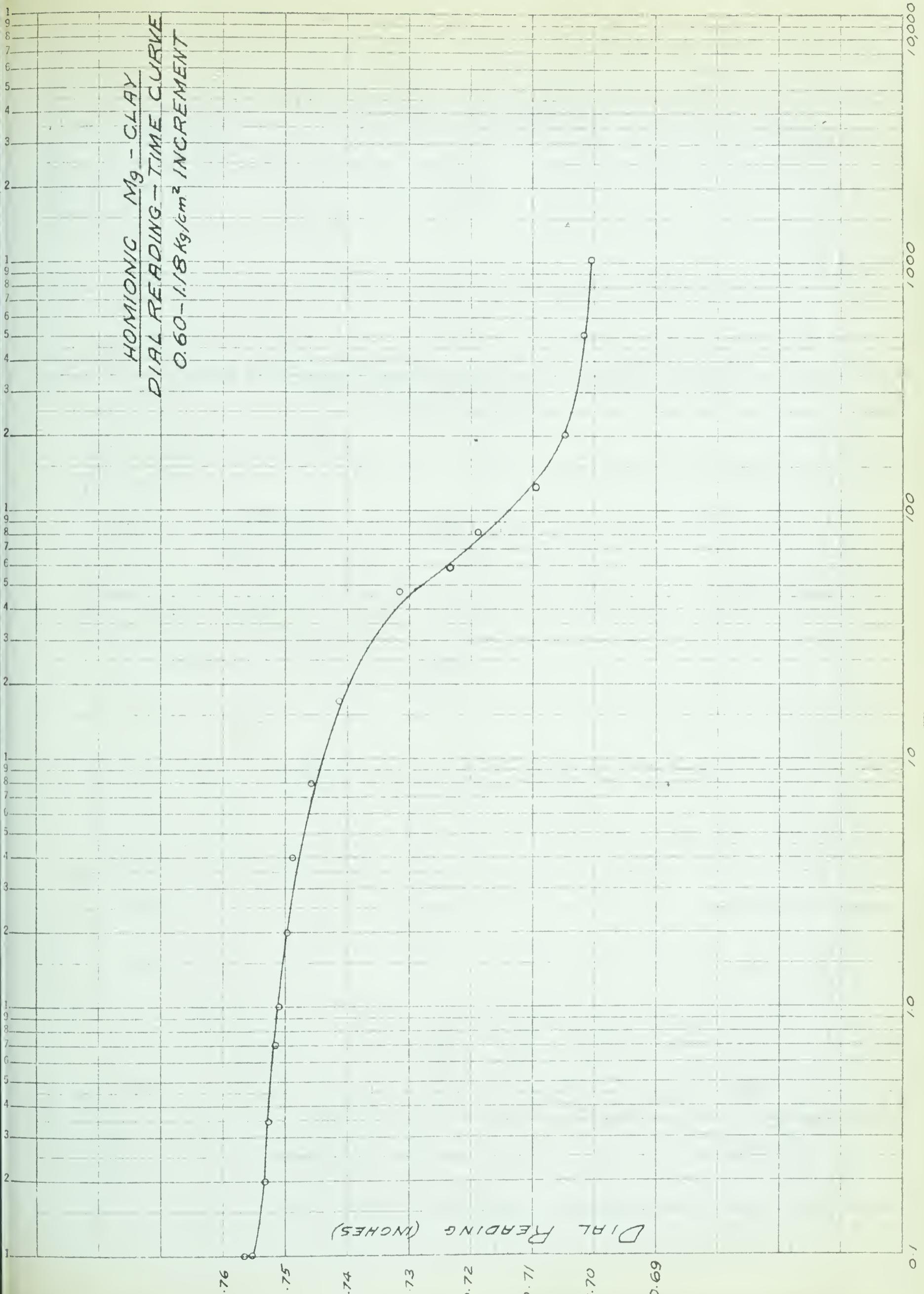
TIME (MINUTES)

10

10

100

1000



APPENDIX C

TEST DATA SHEETS FOR CALCIUM - SODIUM CLAY
MODIFICATIONS

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SOIL MECHANICS
ATTERBERG LIMITS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	94.2% Ca - 5.8% Na Clay
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAMILTON
	DATE 18 Feb 61

Liquid Limit

Trial No.	1	2	3	4	5	
No. of Blows	33	27	24	21	15	
Container No.	V26	A12	V54	V2	V6	
Wt. Sample Wet + Tare	71.5230	77.0631	68.8576	72.6790	87.8454	
Wt. Sample Dry + Tare	68.8706	73.1984	65.3804	69.5914	83.2091	
Wt. Water	2.6524	3.8647	3.4772	3.0876	4.6363	
Tare Container	64.9230	67.5450	60.2990	65.1757	76.7355	
Wt. of Dry Soil	3.9476	5.6534	5.0814	4.4157	6.4736	
Moisture Content w%	67.19	68.36	68.42	69.92	71.62	

Average Values

$$w_l = 68.7$$

$$w_p = 29.5$$

$$w_s = 10.8$$

$$I_p = 39.2$$

$$I_f =$$

$$I_t =$$

Plastic Limit

Trial No.	1	2	3
Container No.	V3	V4	V51
Wt. Sample Wet + Tare	74.2352	66.9246	63.1091
Wt. Sample Dry + Tare	72.4691	66.1219	62.2430
Wt. Water	1.7661	0.8027	0.8661
Tare Container	66.5040	63.4452	59.2390
Wt. of Dry Soil	5.9651	2.6767	3.0040
Moisture Content %	29.61	29.99	28.83

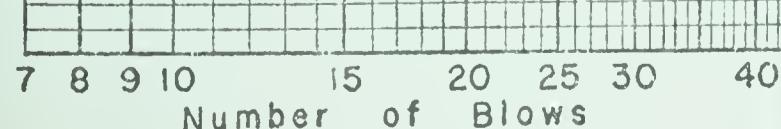
Shrinkage Limit

Trial No.	1	2	3
Container No.	73	75	93
Wt. Sample Wet + Tare	131.81	140.89	143.16
Wt. Sample Dry + Tare	123.97	132.61	135.66
Wt. Water	7.84	8.28	7.50
Tare Container	112.58	120.62	124.78
Wt. of Dry Soil W _o	11.39	11.99	10.88
Moisture Content w% %	68.83	69.06	68.93
Vol. Container V	12.60	13.20	12.10
Vol. Dry Soil Pat V _o	5.98	6.31	5.70
Shrinkage Vol. V-V _o	6.62	6.89	6.40
Shrinkage Limit w _s	10.71	11.60	10.11

$$w_s = w \left(\frac{V - V_o}{V_o} \times 100 \right)$$

Description of Sample: Highly plastic dark brown clay having 94.2% Ca and 5.8% Na cations adsorbed. (%'s based on total cation exchange capacity.)

Remarks:



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ATTERBERG LIMITS

PROJECT THESIS
SITE U. of A.
SAMPLE 86.1% Ca - 13.9% Na Clay
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 17 FEB 61

Liquid Limit

Trial No.	1	2	3	4	5	
No. of Blows	36	28	22	17	14	
Container No.	V54	V6	V26	V2	V58	
Wt. Sample Wet + Tare	71.5663	85.3189	74.9307	72.6790	76.9228	
Wt. Sample Dry + Tare	67.0344	81.8128	70.8297	69.5913	78.8092	
Wt. Water	4.5319	3.4971	4.1010	3.0877	4.1226	
Tare Container	60.2990	76.7355	64.9230	65.1757	66.9360	
Wt. of Dry Soil	6.7354	5.0863	5.9067	4.4156	5.8642	
Moisture Content w%	67.28	68.76	69.43	69.90	70.30	

Average Values

$$w_l = 69.1$$

$$w_p = 30.0$$

$$w_s = 11.3$$

$$I_p = 39.1$$

$$I_f = \underline{\hspace{2cm}}$$

$$I_t = \underline{\hspace{2cm}}$$

Plastic Limit

Trial No.	1	2	3
Container No.	V20	V60	V23
Wt. Sample Wet + Tare	69.7500	65.7472	79.1120
Wt. Sample Dry + Tare	64.4584	64.2245	77.2520
Wt. Water	1.2916	1.5227	1.8600
Tare Container	64.2849	58.9640	71.0930
Wt. of Dry Soil	4.1735	5.2605	6.1590
Moisture Content %	30.94	28.95	30.19

Shrinkage Limit

Trial No.	1	2	3
Container No.	56	80	13
Wt. Sample Wet + Tare	121.79	141.52	131.27
Wt. Sample Dry + Tare	114.01	133.64	123.00
Wt. Water	7.78	7.88	8.27
Tare Container	102.14	121.57	110.25
Wt. of Dry Soil W _o	11.87	12.07	12.75
Moisture Content w%	65.54	65.61	65.86
Vol. Container V	12.60	12.90	13.60
Vol. Dry Soil Pat V _o	6.20	6.25	6.70
Shrinkage Vol. V-V _o	6.40	6.65	6.90
Shrinkage Limit w _s	11.62	10.51	11.75

$$w_s = w \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample: Highly plastic dark brown clay containing 86.1% Ca and 13.9% Na cations adsorbed. (%'s based on total cation exchange capacity).

Remarks:

7 8 9 10 15 20 25 30 40
Number of Blows

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ATTERBERG LIMITS

PROJECT THESIS
SITE U of A.
SAMPLE 71.6% Ca - 28.4% Na Clay
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 19 Feb / 61

Liquid Limit

Trial No.	1	2	3	4	5	
No. of Blows	38	30	23	20	10	
Container No.	A-12	V-26	V-54	V-6	V-2	
Wt. Sample Wet + Tare	76.6984	73.5026	68.7001	85.3190	74.4746	
Wt. Sample Dry + Tare	73.0811	70.0674	65.3061	81.8219	70.6196	
Wt. Water	3.6173	3.4352	3.3940	3.4971	3.8550	
Tare Container	67.5450	64.9230	60.2990	76.7355	65.2695	
Wt. of Dry Soil	5.5361	5.1444	5.0071	5.0864	5.3501	
Moisture Content w%	65.34	66.78	67.78	68.75	72.21	

Average Values

$$w_l = 67.5$$

$$w_p = 28.0$$

$$w_s = 13.0$$

$$I_p = 39.5$$

$$I_f = \text{_____}$$

$$I_t = \text{_____}$$

Plastic Limit

Trial No.	1	2	3
Container No.	V 58	V 39	V 40
Wt. Sample Wet + Tare	72.4582	68.7930	62.5659
Wt. Sample Dry + Tare	71.2277	67.9361	61.6053
Wt. Water	1.2305	0.8569	0.9606
Tare Container	66.9360	64.8020	58.2290
Wt. of Dry Soil	4.2917	3.1341	3.3763
Moisture Content %	28.67	27.34	28.45

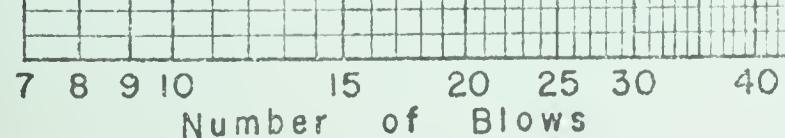
Shrinkage Limit

Trial No.	1	2	3
Container No.	70	44	105
Wt. Sample Wet + Tare	133.75	109.94	144.52
Wt. Sample Dry + Tare	126.00	101.99	136.81
Wt. Water	7.75	7.95	7.71
Tare Container	114.84	90.21	125.79
Wt. of Dry Soil W _o	11.16	11.78	11.02
Moisture Content w% _s	69.44	67.49	69.96
Vol. Container V	12.34	12.50	12.49
Vol. Dry Soil Pot V _o	6.00	6.12	5.90
Shrinkage Vol. V-V _o	6.34	6.38	6.59
Shrinkage Limit w _s	12.63	13.34	10.16

$$w_s = w_r \left(\frac{V - V_o}{V_o} \times 100 \right)$$

Description of Sample: Highly plastic dark brown clay containing 71.6% Ca and 28.4% Na cations adsorbed. (%'s based on total cation exchange capacity.)

Remarks: _____



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SOIL MECHANICS LABORATORY
ATTERBERG LIMITS

PROJECT THESIS
SITE U of A.
SAMPLE 59.9%Ca - 40.1%Na Clay
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 24 Mar/61

Liquid Limit

Trial No.	1	2	3	4	5
No. of Blows	30	30	20	15	16
Container No.	A27	A20	V86	V65	V79
Wt. Sample Wet + Tare	84.459	91.776	90.630	92.559	89.550
Wt. Sample Dry + Tare	74.498	80.848	77.122	80.254	76.396
Wt. Water	9.961	10.928	13.508	12.305	13.154
Tare Container	61.467	66.522	59.877	64.784	69.850
Wt. of Dry Soil	13.031	14.326	17.245	15.470	16.546
Moisture Content w%	76.44	76.28	78.42	79.60	79.50

Average Values

$$w_l = 77.2$$

$$w_p = \text{_____}$$

$$w_s = \text{_____}$$

$$I_p = \text{_____}$$

$$I_f = \text{_____}$$

$$I_t = \text{_____}$$

Plastic Limit

Trial No.

Container No.

Wt. Sample Wet + Tare

Wt. Sample Dry + Tare

Wt. Water

Tare Container

Wt. of Dry Soil

Moisture Content %

Shrinkage Limit

Trial No.

Container No.

Wt. Sample Wet + Tare

Wt. Sample Dry + Tare

Wt. Water

Tare Container

Wt. of Dry Soil W_o

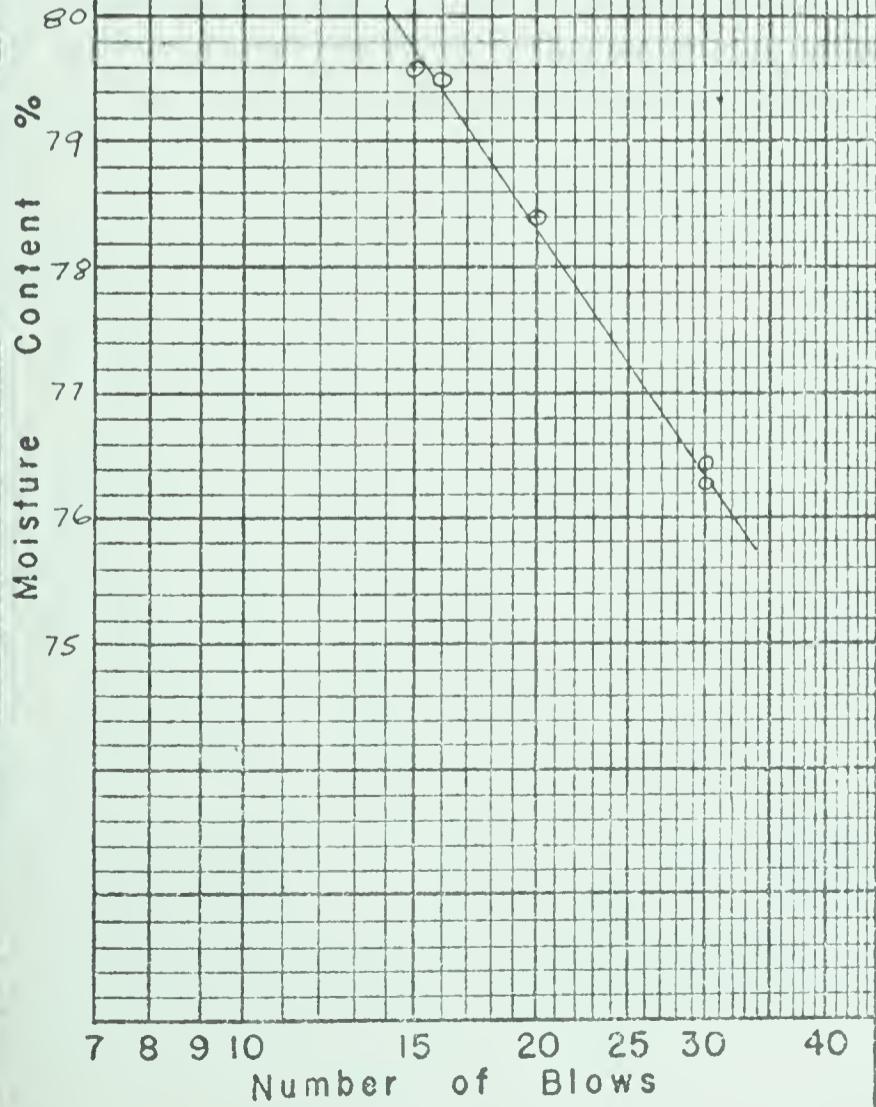
Moisture Content 45%

Vol. Container V

Vol. Dry Soil Pat V_o

Shrinkage Vol. V-V_o

Shrinkage Limit w_s



$$w_s = w \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample: Highly plastic dark brown clay with 59.9% Ca and 40.1% Na cations adsorbed (%'s based on total cation exchange capacity.)

Remarks: Liquid Limit only on this sample.

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SOIL MECHANICS LABORATORY
ATTERBERG LIMITS

PROJECT THESIS
SITE U of A.
SAMPLE 45.6% Ca - 54.4% Na Clay
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 17 Feb 61

Liquid Limit

Trial No.	1	2	3	4	5
No. of Blows	28	27	20	20	15
Container No.	A-12	V-23	V-34	V-40	V-51
Wt. Sample Wet + Tare	76.3845	83.5956	74.9061	70.5920	71.6748
Wt. Sample Dry + Tare	72.2698	77.8276	69.9883	64.8143	65.8026
Wt. Water	4.1147	5.7680	4.9178	5.7777	5.8722
Tare Container	67.4578	71.0930	64.3870	58.2290	59.2390
Wt. of Dry Soil	4.8120	6.7346	5.6013	6.5853	6.5636
Moisture Content w%	85.51	85.65	87.78	87.74	89.46

Average Values

$$w_L = 86.3$$

$$w_{LP} = 29.1$$

$$w_S = 10.8$$

$$I_p = 57.2$$

$$I_f =$$

$$I_L =$$

Plastic Limit

Trial No.	1	2
Container No.	V58	V51
Wt. Sample Wet + Tare	70.9632	65.0966
Wt. Sample Dry + Tare	70.0624	63.7633
Wt. Water	0.9008	1.3333
Tare Container	66.9360	59.2390
Wt. of Dry Soil	3.1264	4.5243
Moisture Content %	28.83	29.47

Shrinkage Limit

Trial No.	1	2	3
Container No.	67	81	76
Wt. Sample Wet + Tare	126.49	118.63	135.75
Wt. Sample Dry + Tare	118.10	109.62	127.37
Wt. Water	8.39	9.01	8.38
Tare Container	108.62	99.21	117.86
Wt. of Dry Soil W _o	9.48	10.41	9.51
Moisture Content w%	88.50	86.55	88.20
Vol. Container V	12.40	12.70	12.40
Vol. Dry Soil Pat V _o	4.98	5.50	5.10
Shrinkage Vol. V-V _o	7.42	7.20	7.30
Shrinkage Limit w _s	10.23	17.78	11.44

$$w_s = w \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample: Highly plastic dark brown clay - containing 45.6% Ca and 54.4% Na cations adsorbed (%'s based on total cation exchange capacity).

Remarks:

7 8 9 10 15 20 25 30 40
Number of Blows

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SOIL MECHANICS LABORATORY
ATTERBERG LIMITS

PROJECT THESIS
SITE U of A
SAMPLE 22.1% Ca - 77.9% Na Clay
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE 20 Feb 61

Liquid Limit

Trial No.	1	2	3	4	5
No. of Blows	31	34	28	16	17
Container No.	V6	V2	V16	V11	V20
Wt. Sample Wet + Tare	85.7396	74.4441	75.8752	73.6373	76.3426
Wt. Sample Dry + Tare	81.5669	70.1432	70.4879	68.4199	70.6099
Wt. Water	4.1727	4.3009	5.3873	5.2174	5.7327
Tare Container	76.7355	65.1757	64.3008	62.6874	64.2849
Wt. of Dry Soil	4.8314	4.9675	6.1871	5.7235	6.3250
Moisture Content w%	86.36	86.58	87.07	91.01	90.63

Average Values

$$w_l = 88.2$$

$$w_p = 30.2$$

$$w_s = 11.3$$

$$I_p = 58.0$$

$$I_f = \underline{\quad}$$

$$I_t = \underline{\quad}$$

Plastic Limit

Trial No.	1	2
Container No.	V60	V3
Wt. Sample Wet + Tare	65.3969	71.5050
Wt. Sample Dry + Tare	63.9160	70.3406
Wt. Water	1.4809	1.1644
Tare Container	58.9640	66.5040
Wt. of Dry Soil	4.9520	3.8366
Moisture Content %	29.90	30.35

Shrinkage Limit

Trial No.	1	2	3
Container No.	47	97	90
Wt. Sample Wet + Tare	131.32	139.46	139.89
Wt. Sample Dry + Tare	122.54	130.76	113.15
Wt. Water	8.78	8.70	8.74
Tare Container	113.91	122.28	122.64
Wt. of Dry Soil W _o	8.63	8.48	8.51
Moisture Content w% _o	101.73	102.59	102.70
Vol. Container V	12.50	12.30	13.40
Vol. Dry Soil Pat V _o	4.69	4.70	4.50
Shrinkage Vol. V-V _o	7.81	7.60	7.90
Shrinkage Limit w _s	11.23	12.99	9.87

$$w_s = w_p \left(\frac{V - V_o}{W_o} \times 100 \right)$$

Description of Sample: Highly plastic dark brown clay - containing 22.1% Ca and 77.9% Na cations adsorbed. (%'s based on total cation exchange capacity).

Remarks:

7 8 9 10 15 20 25 30 40
Number of Blows

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CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	94.2% Ca - 5.8% Na Clay
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAMILTON
	DATE MAR 3/6

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2700$ ins.

$$\text{Void Ratio } e(\text{End}) = \underline{1.3500}$$

Void Ratio $e(\text{Start}) = \underline{2.3123}$

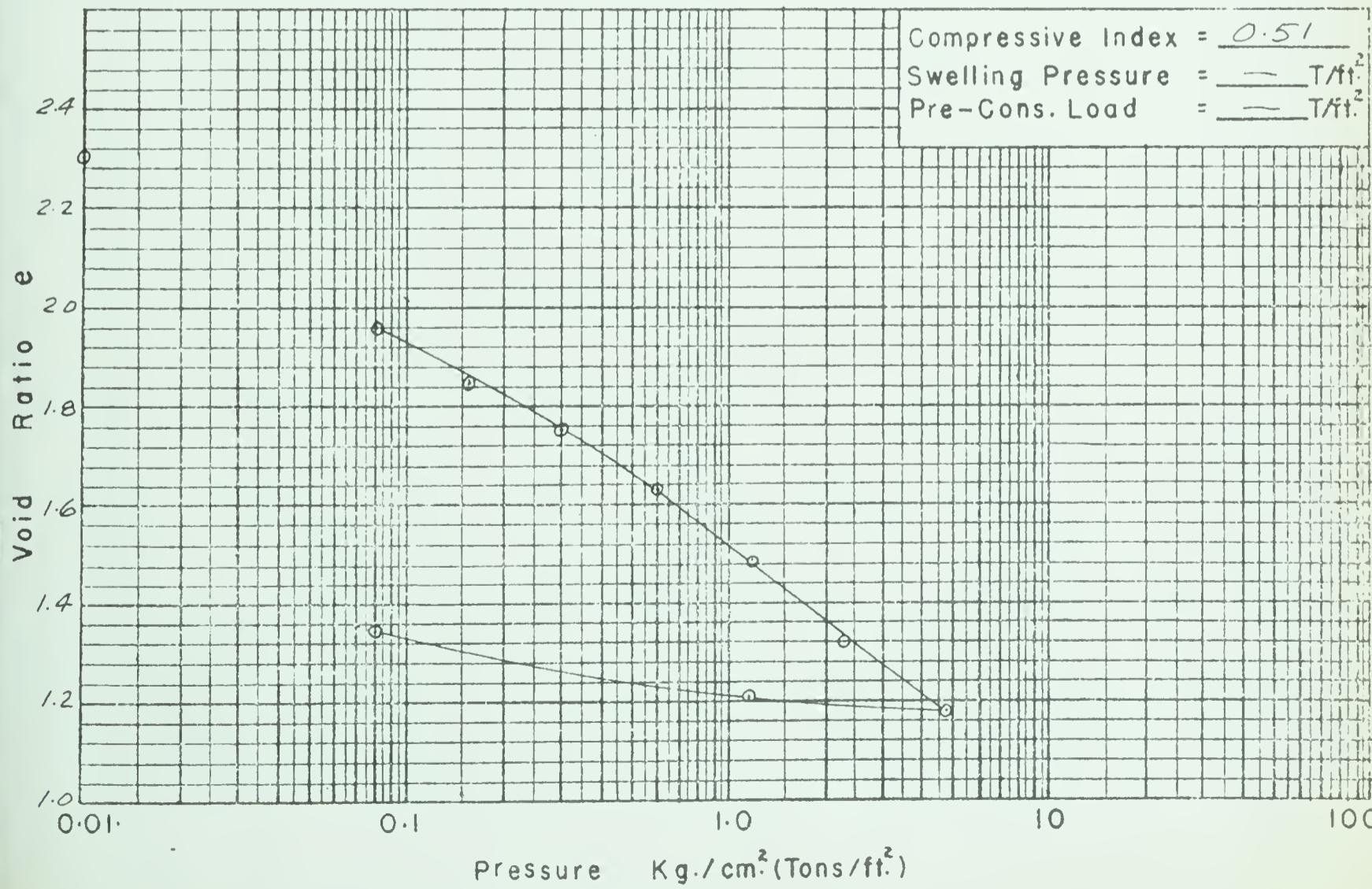
Void Ratio e (Start Dimensions) = 2.2080

$$e(End) = W\%(End) \times G_s$$

$$H_s = \left(\frac{Wt \cdot Soil}{G_s \times Area \times 2.54} \right) ins.$$

$$e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = T/\text{ft}^2$
	0	0.9000	0	0	2.3123	0
1 Day	50	8041	0.0959	0.3550	1.9573	0.08
2 Days	100	7750	0.291	1077	1.8496	0.16
1 Day	200	7472	0.278	1029	1.7467	0.30
1 Day	400	7170	0.302	1118	1.6349	0.60
1 Day	800	6770	0.400	1481	1.4868	1.18
1 Day	1600	6310	0.460	1703	1.3165	2.35
1 Day	3200	5947	0.363	1343	1.1822	4.70
2 Days	800	6010	0.063	0234	1.2056	1.18
3 Days	50	6400	0.390	1444	1.3500	0.08



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CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	86.1% Ca - 13.9% Na Clay
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAMILTON
	DATE APR. 1/61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2935$ ins.

Void Ratio e (End) = 1.3350

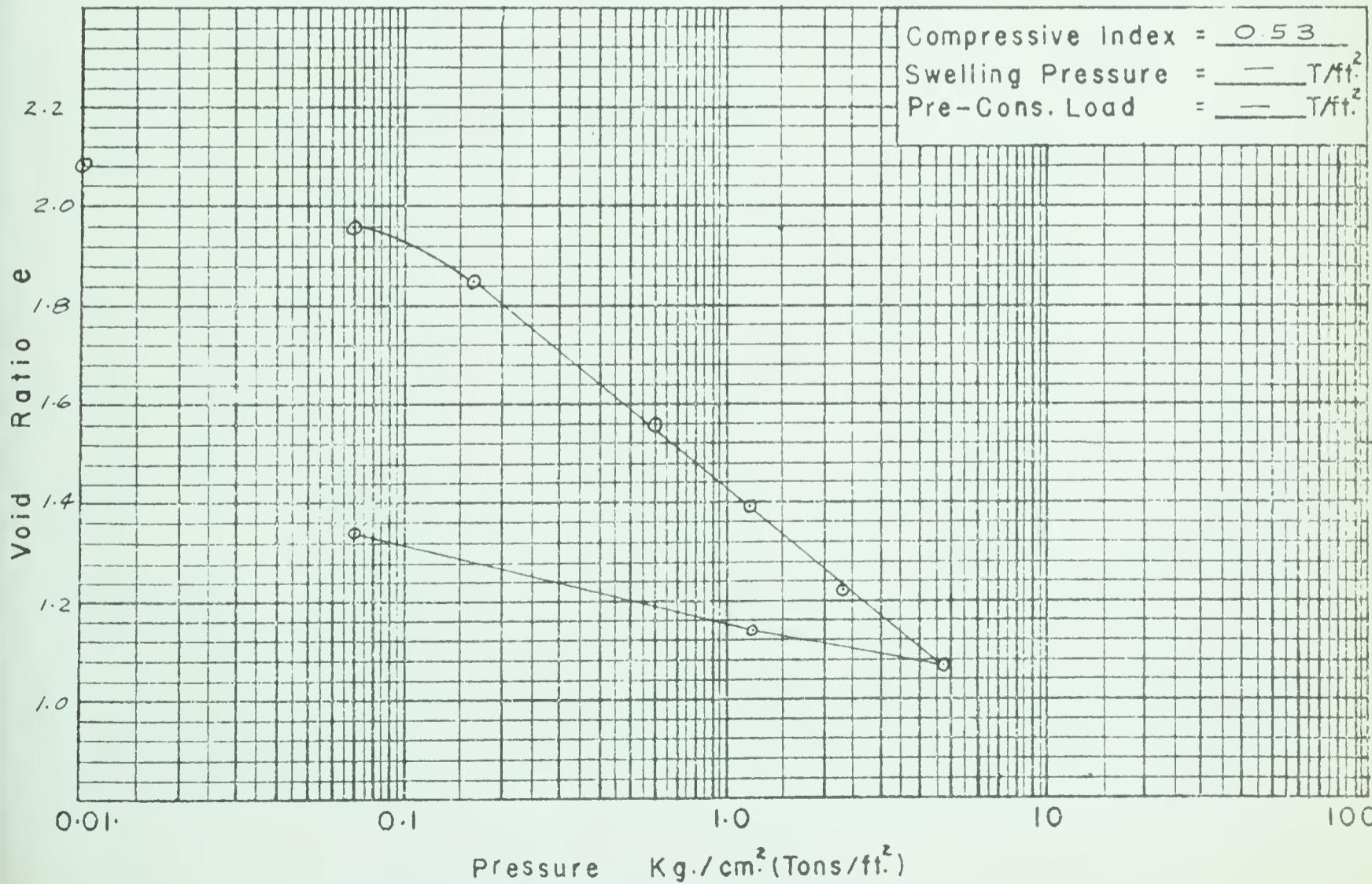
Void Ratio $e(\text{Start}) = \underline{2.0852}$

Void Ratio e (Start Dimensions) =

$$e(End) = W\% (End) \times G_s \quad H_s = \left(\frac{Wt \cdot Soil}{G_s \times Area \times 2.54} \right) ins.$$

$$e = \text{previous } e \pm \frac{\text{Def'l.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = T/\text{ft}^2$
	0	0.6500	0	0	2.0852	0
2 Days	20	6119	0.0381	0.1299	1.9553	0.07
2 Days	50	5797	0.0322	0.1097	1.8456	0.16
1 Day	200	4967	0.0830	0.2830	1.5626	0.60
✓	400	4470	0.0497	0.1695	1.3931	1.18
✓	800	3977	0.0493	0.1682	1.2249	2.35
✓	1600	3527	0.0450	0.1532	1.0717	4.69
✓	400	3721	0.0194	0.0661	1.1378	1.18
2 Days	20	4300	0.0579	0.1972	1.3350	0.07



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CONSOLIDATION RESULTS

PROJECT THESIS
SITE U. of A.
SAMPLE 84.9% Ca - 15.1% Na clay
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE MAR 3/61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2636$ ins.

Void Ratio e (End) = 1.3320

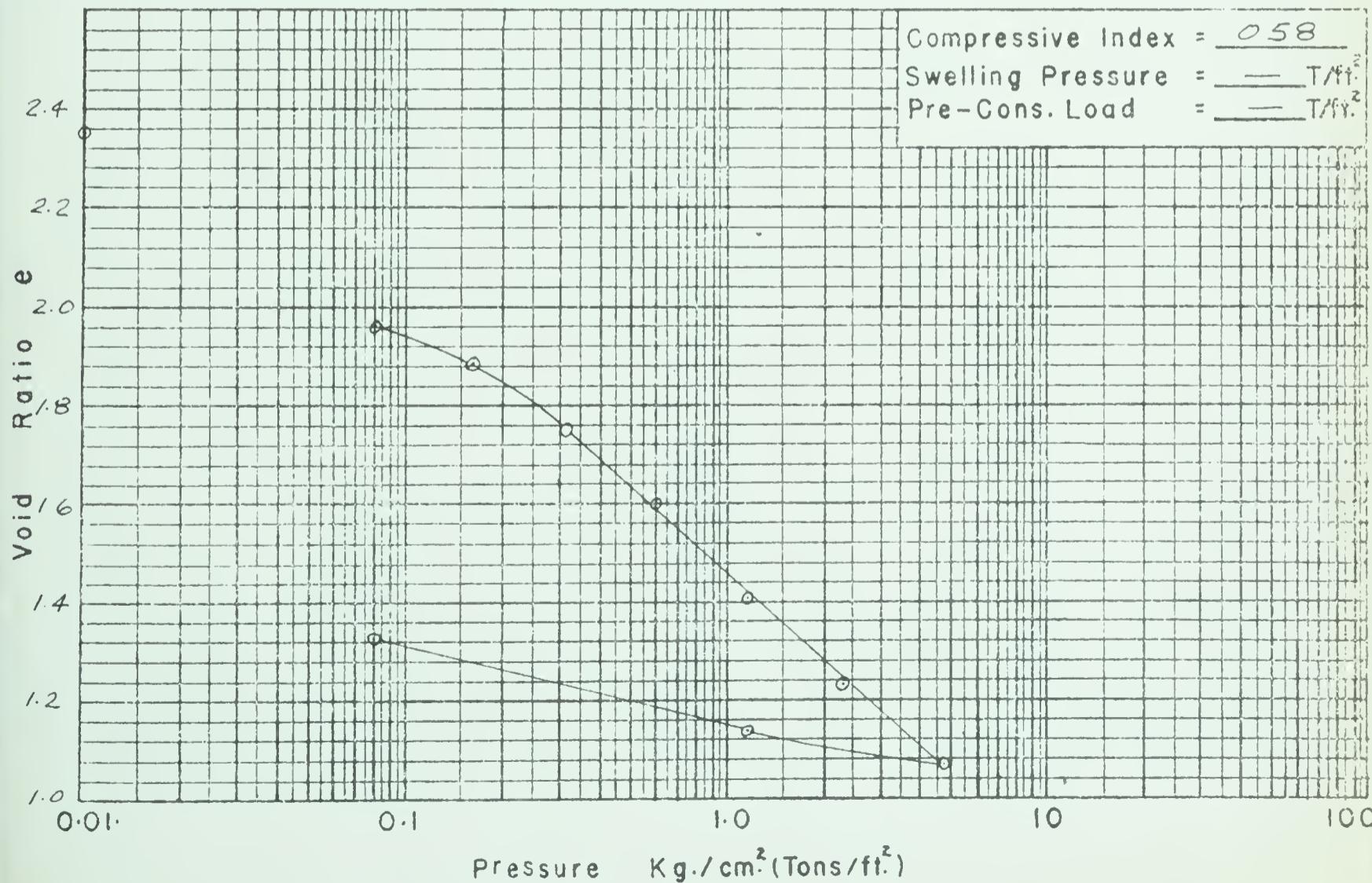
Void Ratio $e(\text{Start}) = 2.3501$

Void Ratio e (Start Dimensions) = _____

$$e(End) = W\% (End) \times G_s \quad H_s = \left(\frac{Wt \cdot Soil}{G_s \times Area \times 2.54} \right) ins.$$

$$e = \text{previous } e \pm \frac{\text{Def'l.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection	Void Ratio e	Pressure Kg/cm ² = T/ft. ²
				H _s		
	0	0.9000	0	0	2.3501	0
3 Days	50	7964	0.1036	0.3930	1.9571	0.08
1 Day	100	7799	0.0165	0.0626	1.8945	0.16
2 Days	200	7422	0.0377	0.1430	1.7515	0.31
2 Days	400	7021	0.0401	0.1524	1.5991	0.60
1 1/2 Days	800	6535	0.0486	0.1847	1.4144	1.18
1 Day	1600	6062	0.0473	0.1796	1.2348	2.35
1 Day	3200	5630	0.0432	0.1640	1.0708	4.70
2 Days	800	5812	0.0182	0.0690	1.1398	1.18
2 Days	50	6318	0.0506	0.1922	1.3320	0.08



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CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	79.9% Ca - 20.1% Na Clay.
LOCATION	
HOLE	DEPTH
TECHNICIAN	DATE
HAMILTON	APRIL 16

Specific Gravity of Soil Solids G_s = 2.76 Height of Soil Solids H_s = 0.3076 ins.

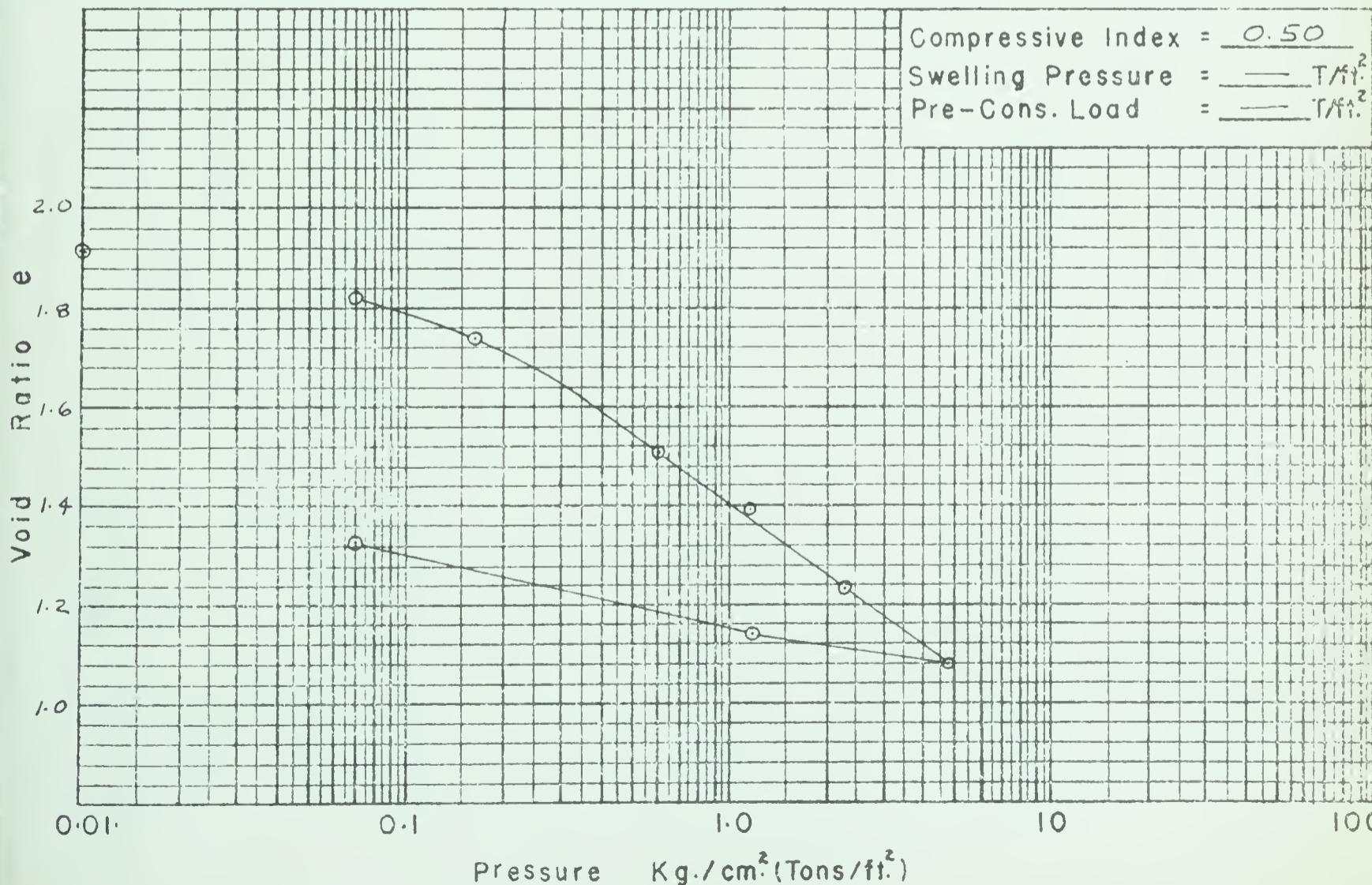
$$\text{Void Ratio } e(\text{End}) = 1.3340$$

Void Ratio $e(\text{Start}) = \underline{1.9188}$

Void Ratio e (Start Dimensions) =

$$e(\text{End}) = W\%(\text{End}) \times G_s \quad H_s = \left(\frac{Wt \cdot \text{Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.} \quad e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = T/\text{ft}^2$
	0	0.8000	0	0	1.9188	0
2 Days	20	7702	0.0298	0.0969	1.8219	0.07
2 Days	50	7445	0.0257	0.0836	1.7381	0.16
1 Day	200	6760	0.0685	0.2228	1.5153	0.60
✓	400	6313	0.0347	0.1129	1.3924	1.18
✓	800	5822	0.0491	0.1600	1.2324	2.35
✓	1600	5364	0.0458	0.1491	1.0833	4.69
✓	400	5551	0.0187	0.0609	1.1442	1.18
2 Days	20	6135	0.0584	0.1889	1.3340	0.07
			1	1		



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CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U of A
SAMPLE	71.6% Ca - 28.4% Na Clay
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAMILTON
	DATE MARIO/61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2705$ ins.

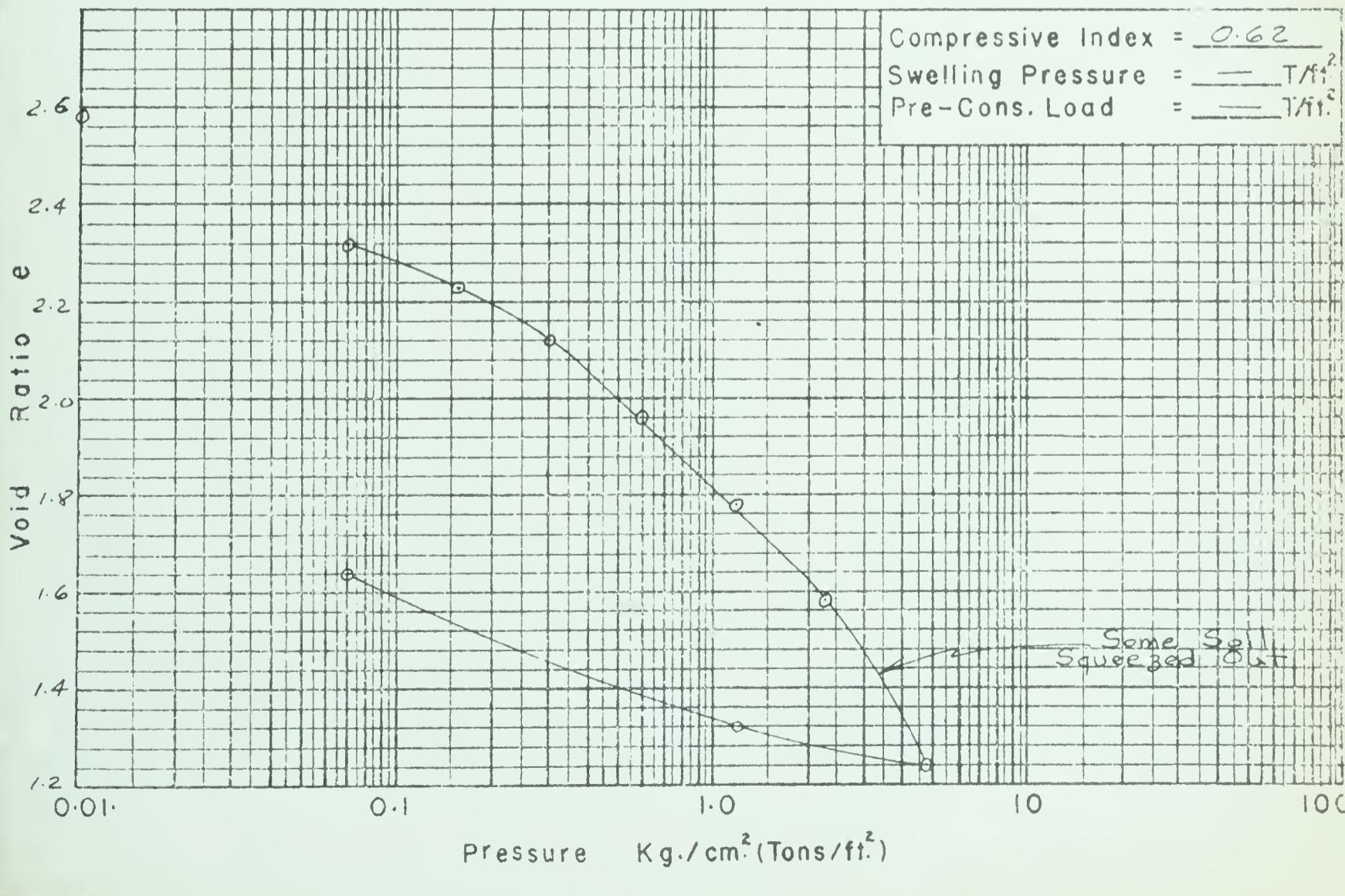
Void Ratio $e(\text{End}) = 1.6390$

Void Ratio $e(\text{Start}) = 2.5753$

Void Ratio $e(\text{Start Dimensions}) =$

$$e(\text{End}) = W\%(\text{End}) \times G_s \quad H_s = \left(\frac{\text{Wt. Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.} \quad e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = \text{T/ft}^2$
0	0.9500	0	0	0	2.5753	0
20	0.8810	0.0690	0.2545	0.0913	2.3208	0.07
50	0.8563	0.0247	0.0913	0.02295	2.2295	0.16
100	0.8260	0.0303	0.1119	0.01176	2.1176	0.30
200	0.7831	0.0429	0.1585	0.01585	1.9591	0.60
400	0.7348	0.0483	0.1782	0.01782	1.7809	1.18
800	0.6808	0.0540	0.1993	0.01993	1.5816	2.35
1600	0.5885	0.0923	0.3410	0.03410	1.2406	4.69
400	0.6103	0.0218	0.0806	0.00806	1.3218	1.18
20	0.6963	0.0860	0.3178	0.03178	1.6390	0.07



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CONSOLIDATION RESULTS

PROJECT	THESIS
SITE	U. of A.
SAMPLE	45.6% Ca - 54.4% Na Clay
LOCATION	
HOLE	
TECHNICIAN	HAMILTON
DEPTH	
DATE APRIL 1/61	

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2594$ ins.

Void Ratio e (End) = 1.4410

Void Ratio e (Start) = 2.2049

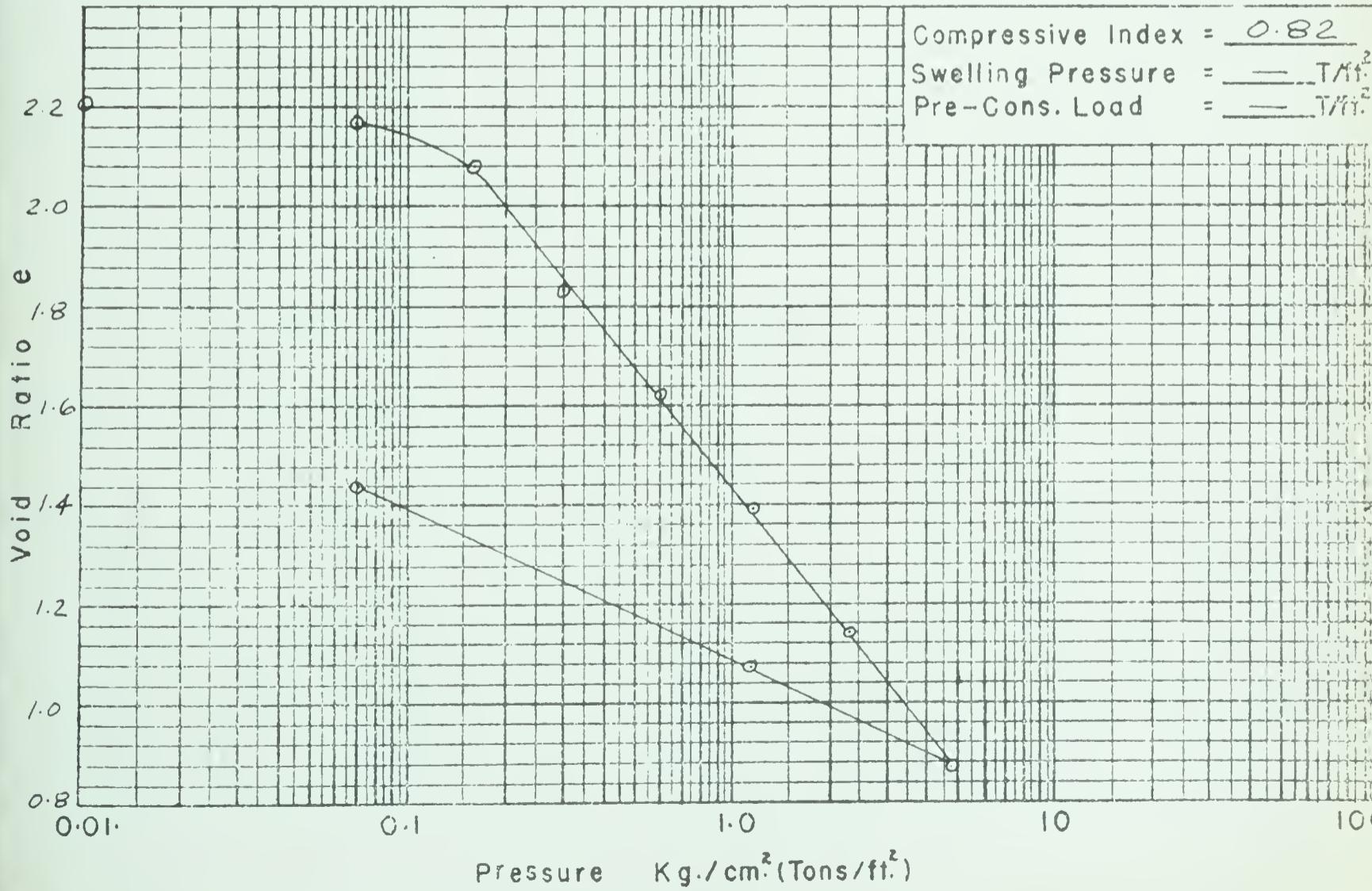
Void Ratio e (Start Dimensions) =

e (End) = $W\% \times (End) \times G_s$

$$H_s = \frac{W \cdot \text{Soil}}{G_s \times \text{Area} \times 2.54} \text{ ins.}$$

$$e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = \text{T/ft}^2$
	0	0.8000	0	0	2.2049	0
2 Days	20	0.7910	0.0090	0.0347	2.1702	0.07
1 Day	50	0.7684	0.226	0.0871	2.0831	0.16
3 Days	100	0.7039	0.645	0.2485	1.8346	0.30
3 Days	200	0.6489	0.550	0.2120	1.6226	0.60
4 Days	400	0.5878	0.611	0.2356	1.3870	1.18
4 Days	800	0.5235	0.643	0.2478	1.1392	2.35
4 Days	1600	0.4531	0.704	0.2710	0.8682	4.69
3 Days	400	0.5060	0.529	0.2038	1.0720	1.18
2 Days	20	0.6018	0.0958	0.3690	1.4410	0.07



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CONSOLIDATION RESULTS

PROJECT THESIS
SITE J. of A
SAMPLE 22.1% Ca - 77.9% Na Clay.
LOCATION
HOLE DEPTH
TECHNICIAN HAMILTON DATE APRIL 2/61

Specific Gravity of Soil Solids $G_s = 2.76$ Height of Soil Solids $H_s = 0.2471$ ins.

Void Ratio e (End) = 2.1765

Void Ratio e (Start) = 2.7856

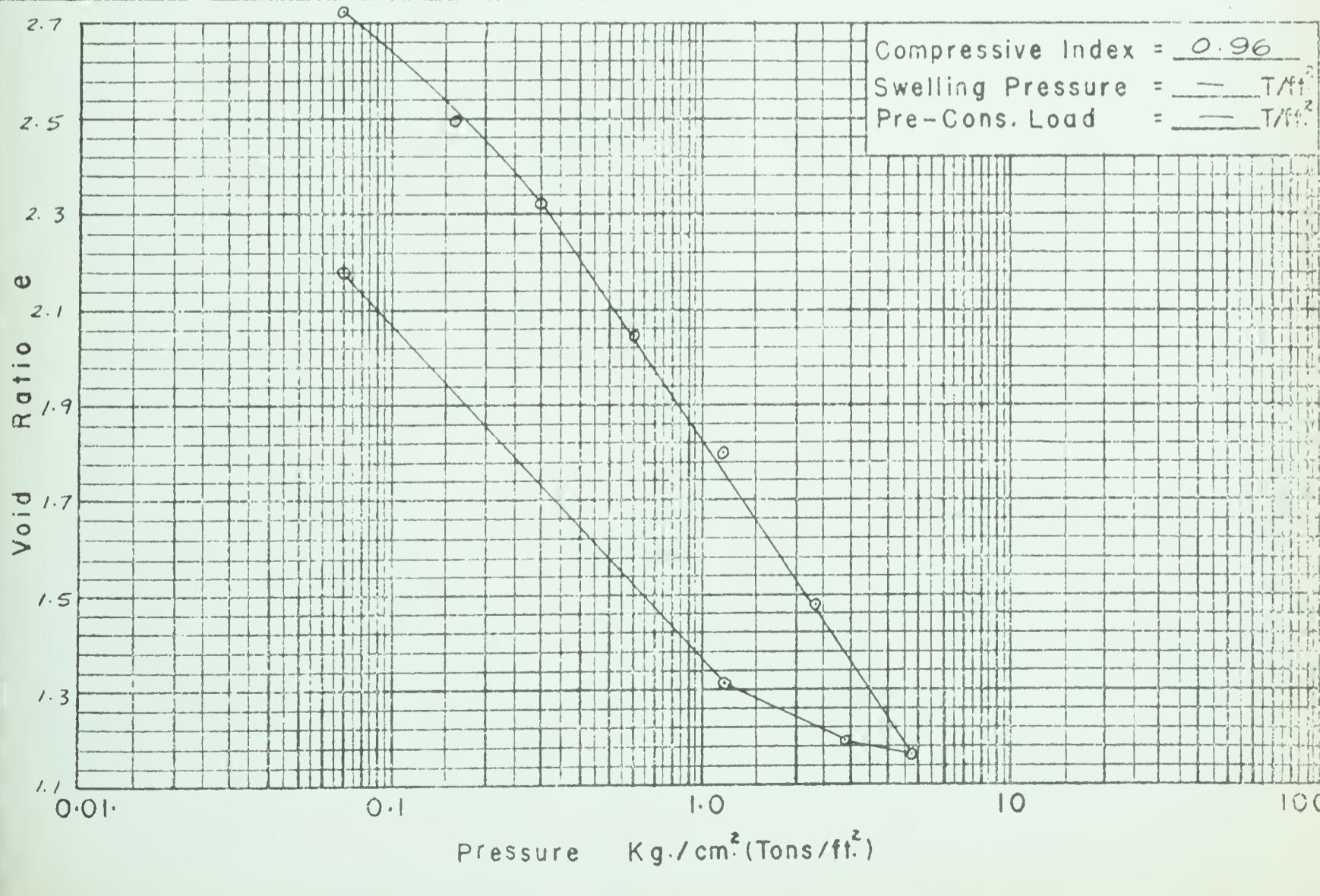
Void Ratio e (Start Dimensions) =

e (End) = $W\%(\text{End}) \times G_s$

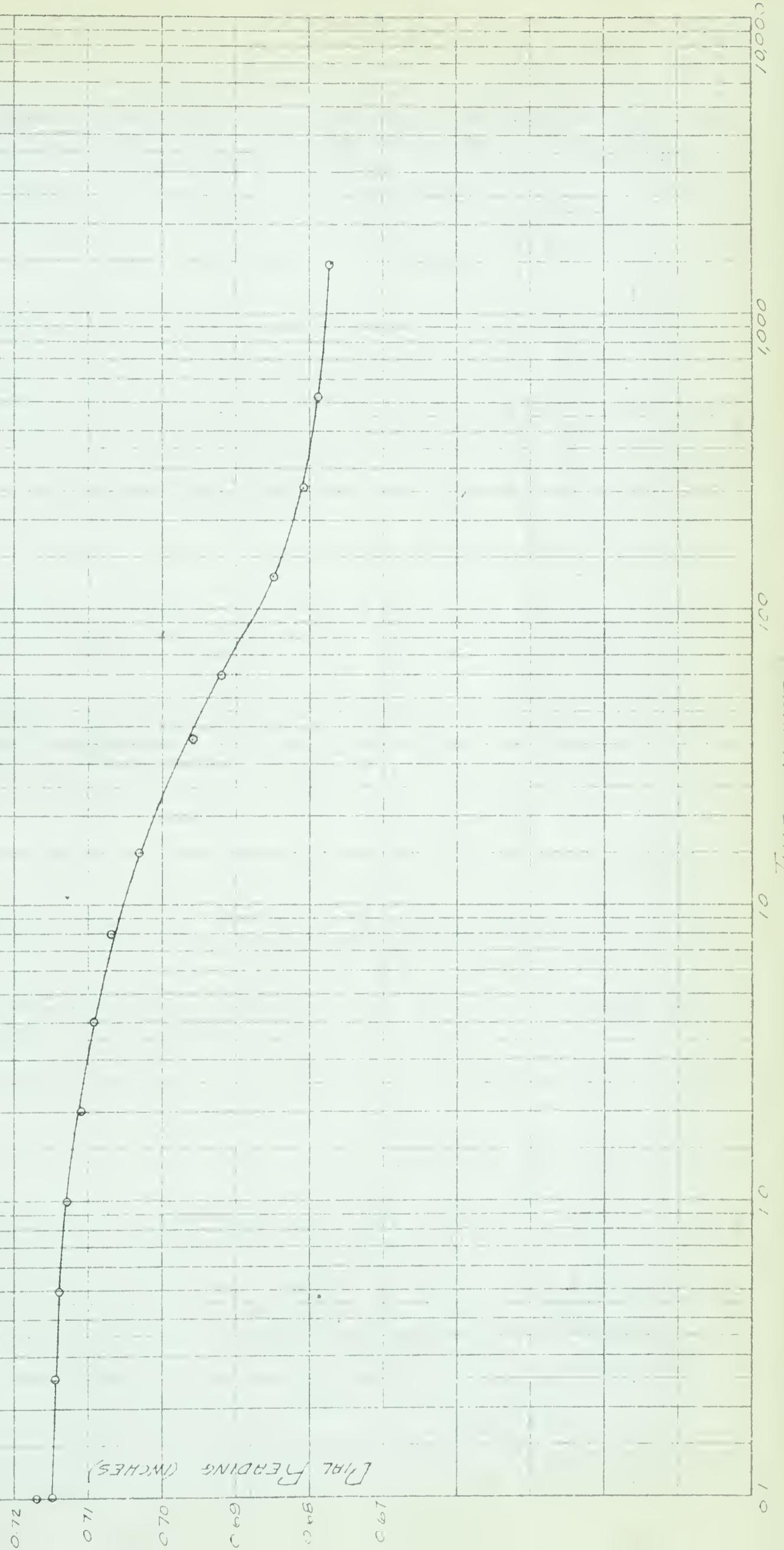
$$H_s = \left(\frac{Wt. \text{ Soil}}{G_s \times \text{Area} \times 2.54} \right) \text{ins.}$$

$$e = \text{previous } e \pm \frac{\text{Defl.}}{H_s}$$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection H_s	Void Ratio e	Pressure $\text{Kg/cm}^2 = \text{T/ft}^2$
	0	0.9400	0	0	2.7856	0
2 Days	20	0.9260	0.0140	0.0567	2.7289	0.07
4 Days	50	0.8675	0.0585	0.2365	2.4924	0.16
3 Days	100	0.8261	0.0414	0.1675	2.3249	0.30
5 Days	200	0.7580	0.0681	0.2755	2.0494	0.60
4 Days	400	0.6956	0.0624	0.2524	1.7970	1.18
4 Days	800	0.6175	0.0781	0.3160	1.4810	2.35
3 Days	1600	0.5480	0.0795	0.3220	1.1590	4.69
1 Day	1000	0.5567	0.0087	0.0352	1.1915	2.91
1 Day	400	0.5861	0.0294	0.1190	1.3105	1.18
5 Days	20	0.8001	0.2140	0.8660	2.1765	0.07



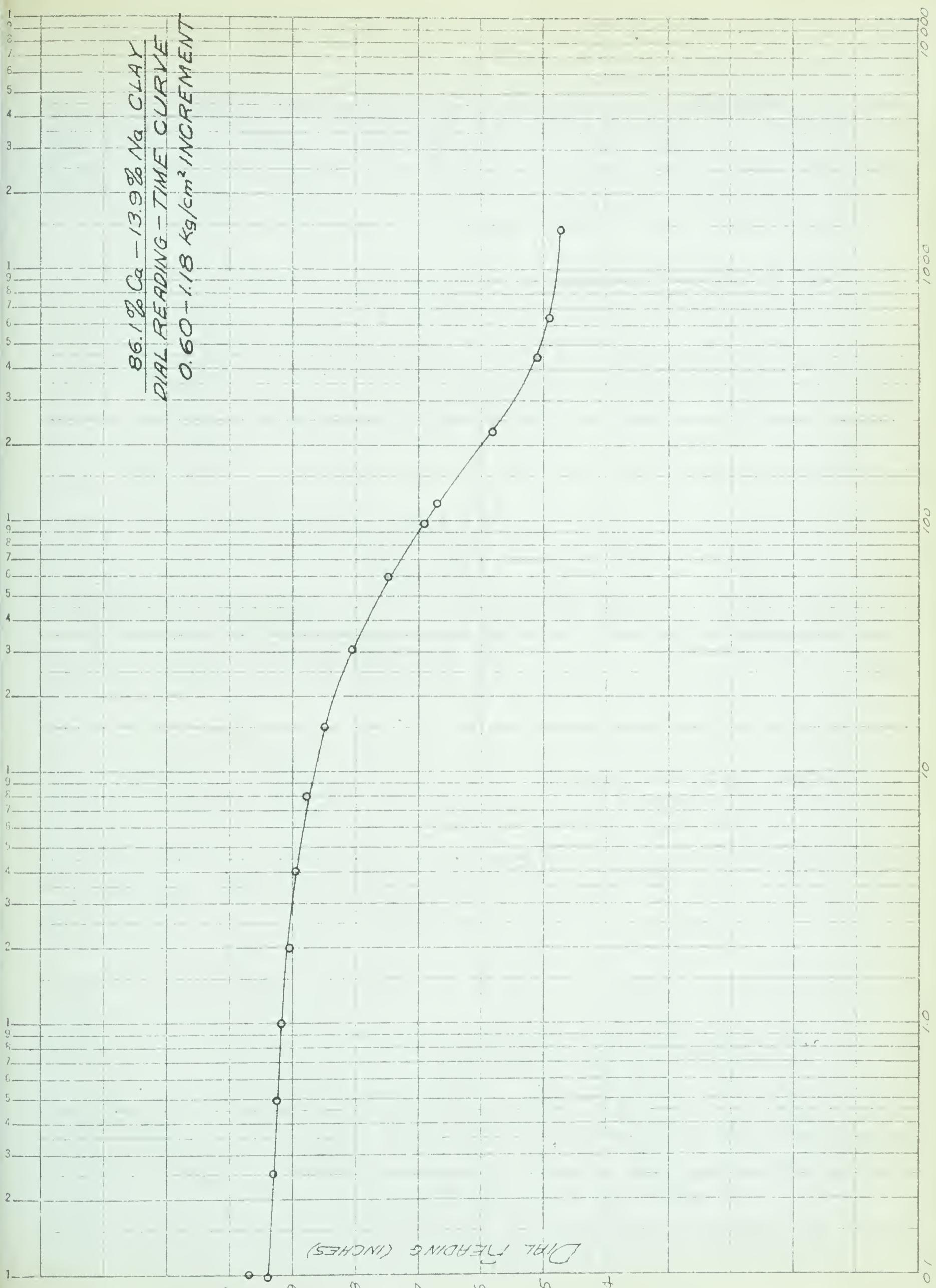
94.2% Ca - 5.8% Na CLAY
0.60 - 1.19 kg/cm² INCREMENT
DIAL READING - TIME CURVE



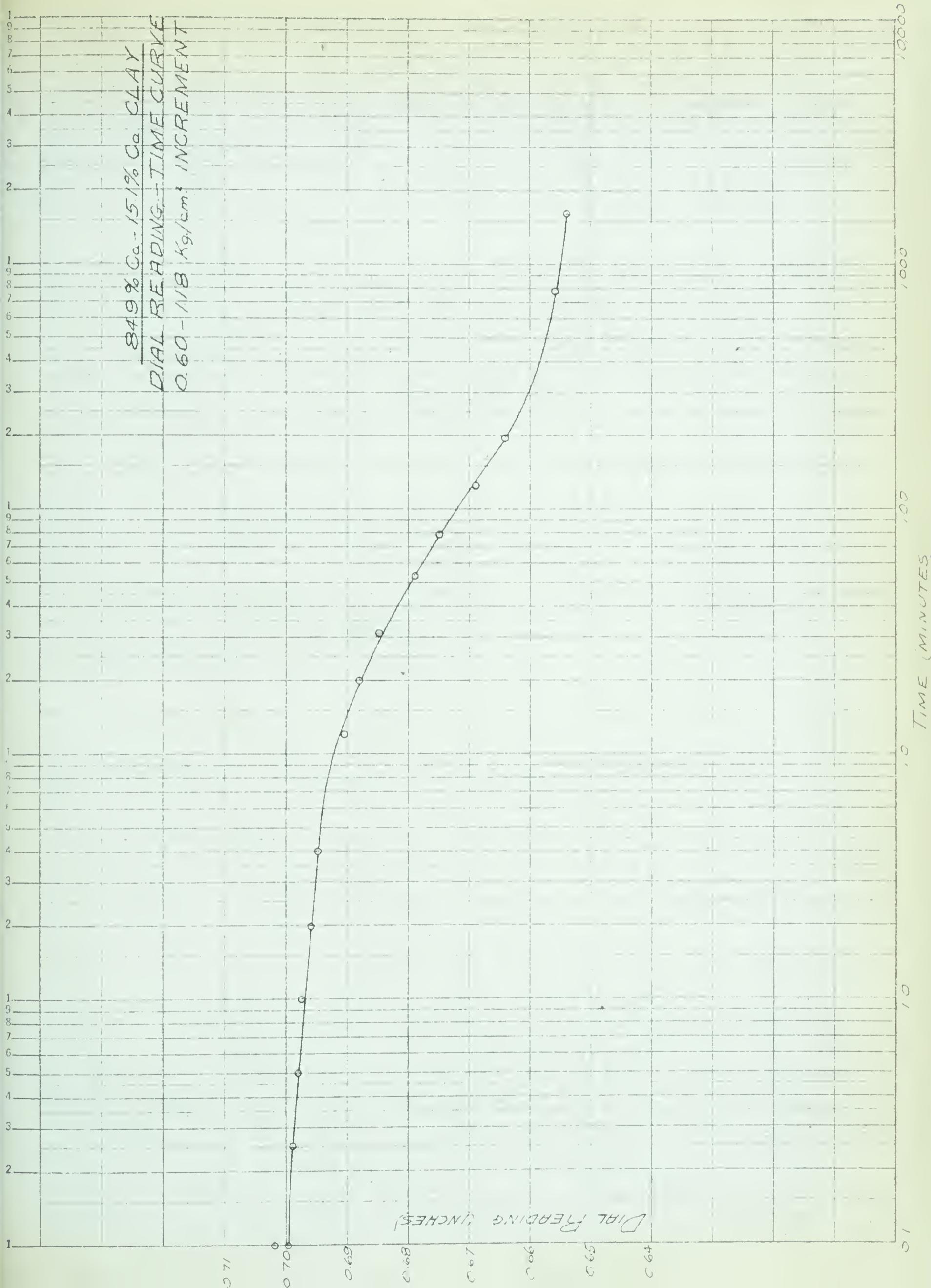
86.1% Ca - 13.9% Na CLAY
DIAL READING - TIME CURVE
0.60 - 1.18 kg/cm² INCREMENT

DIAL READING (INCHES)

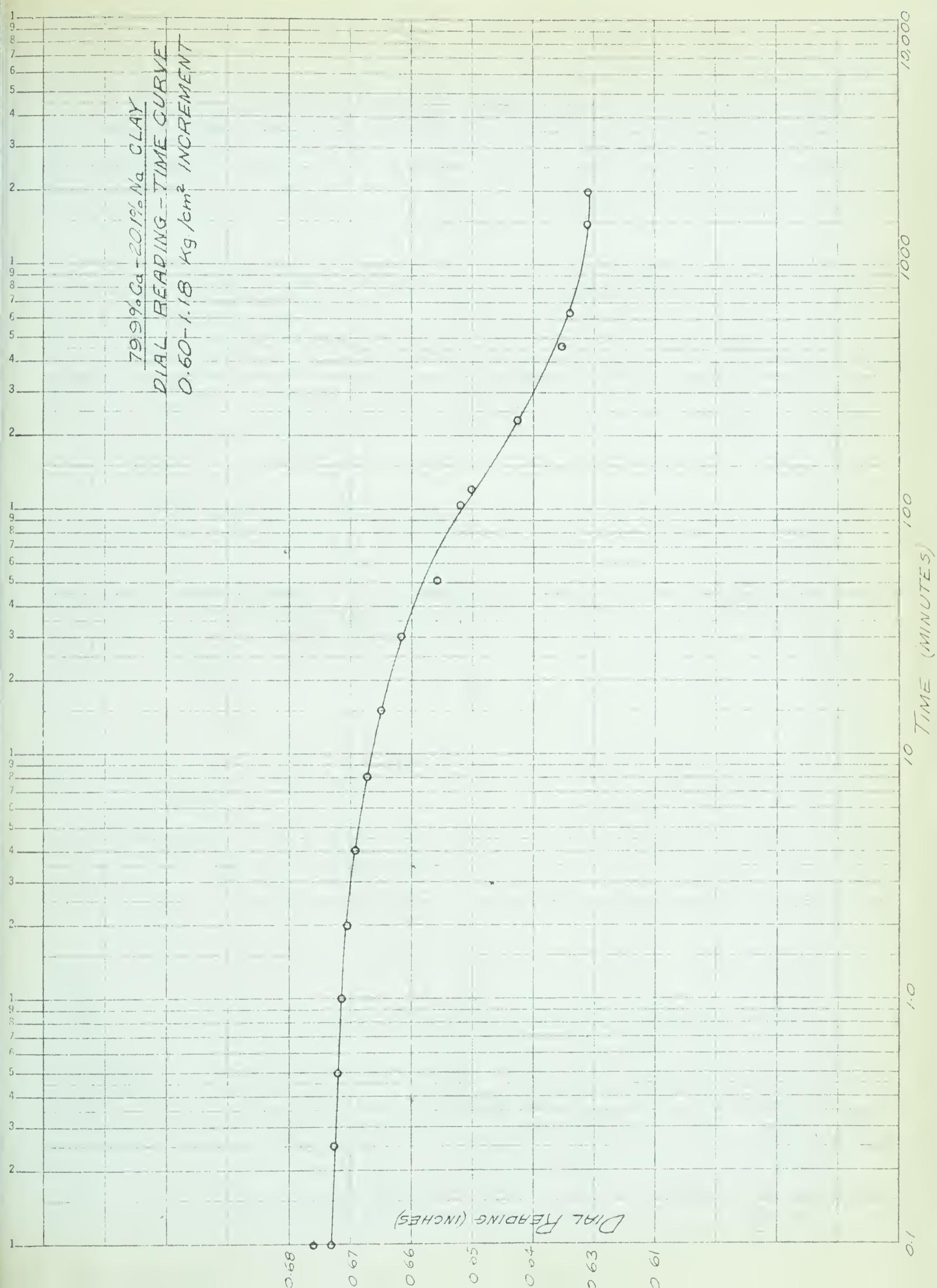
TIME (MINUTES)



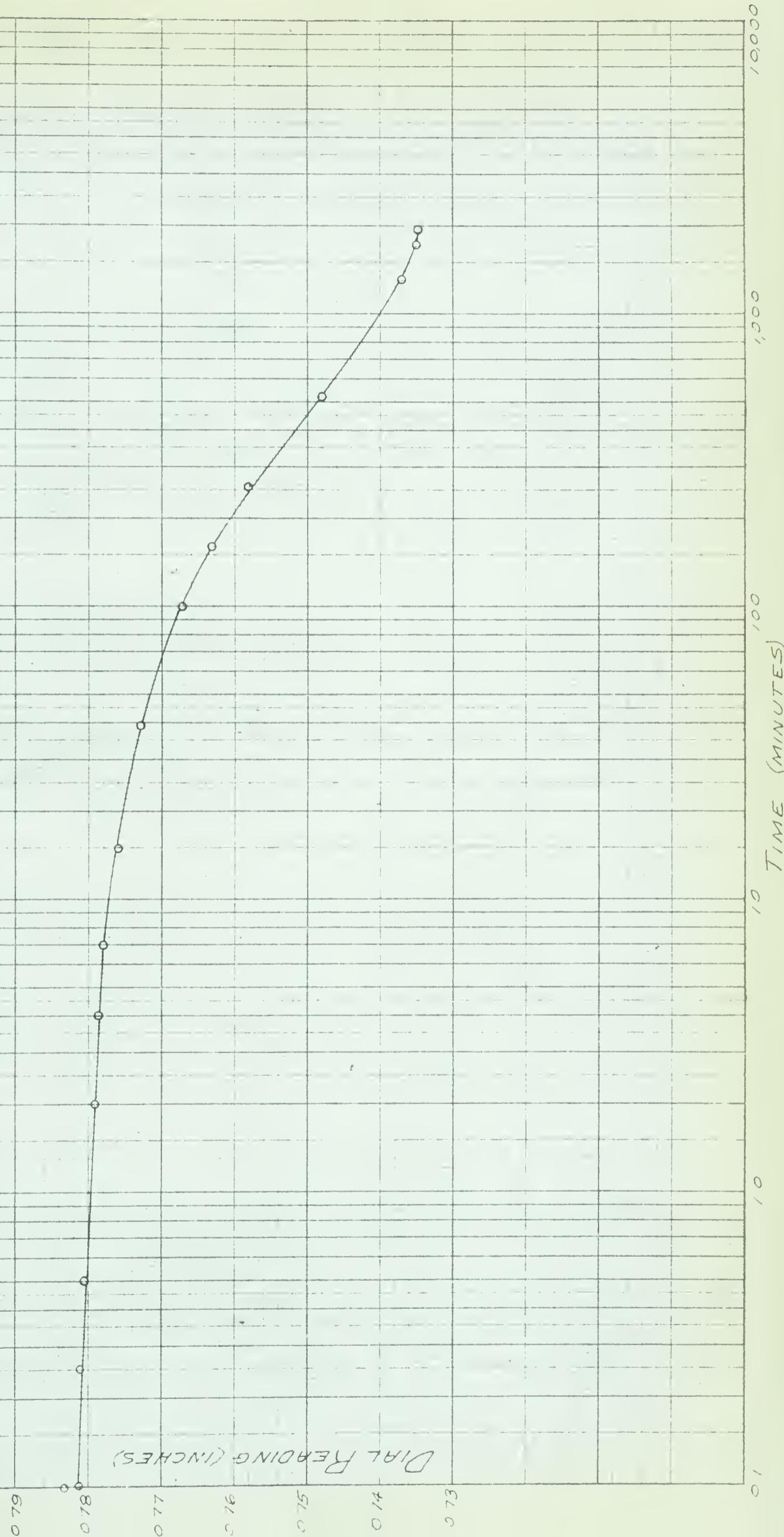
84.9% Ca - 15.1% Ca₃Cl₂
DIAL READING + TIME CURVE
0.60 - 1/8 Kg/cm² INCREMENT



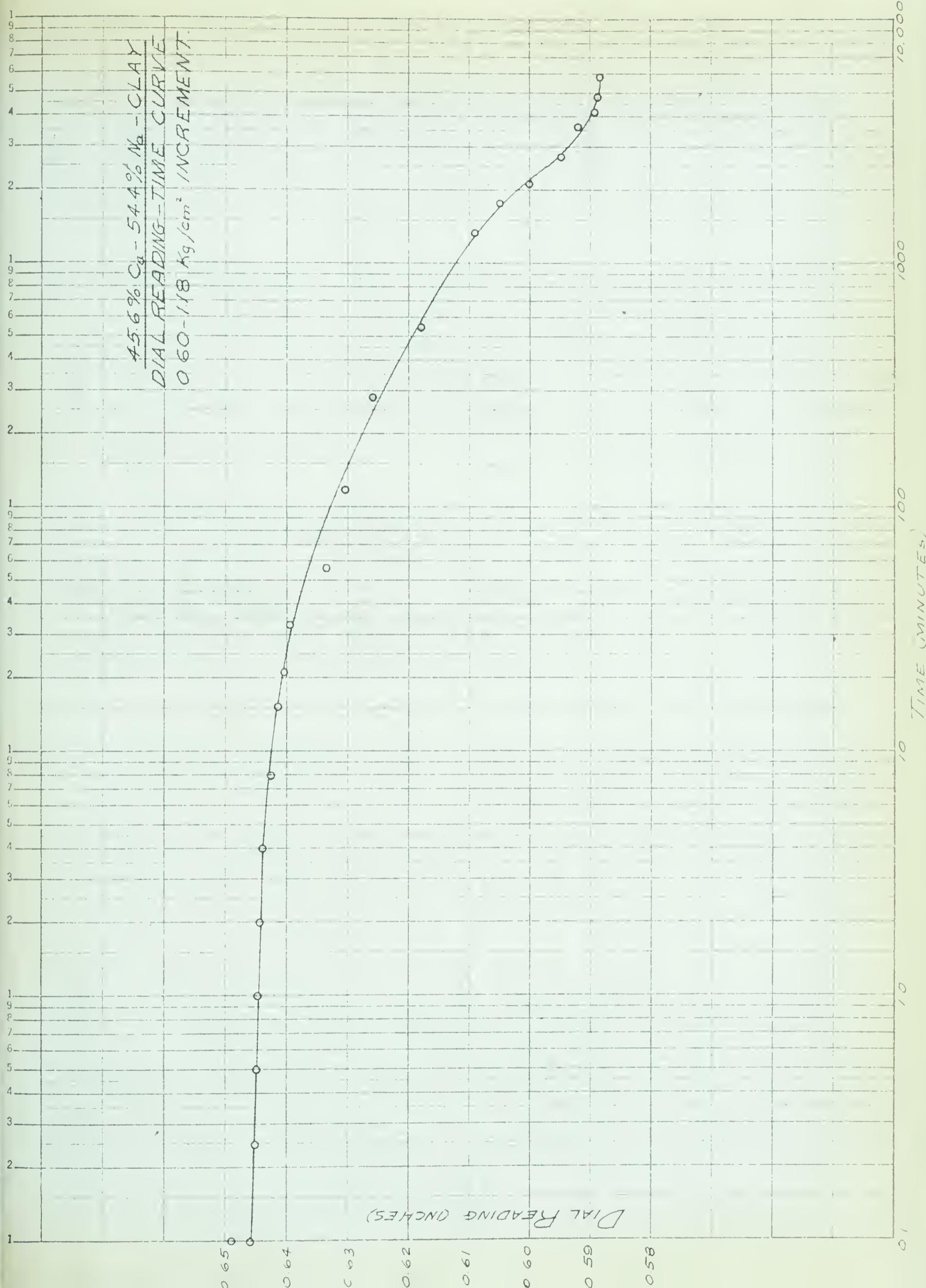
79.9% Ca + 20.1% Na CLAY
DIAL READING - TIME CURVE
0.60-1.18 Kg/cm² INCREMENT



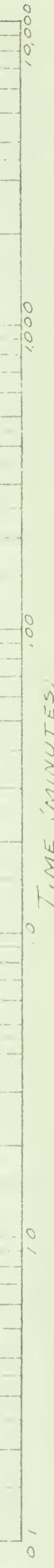
71.6% Ca-25.4% Na CLAY
DIAL READING - TIME CURVE
0.60 - 1.18 Kg/cm² INCREMENT



45.6% Ca - 54.4% N - CLAY
DIAL READING - TIME CURVE
0.60 - 1.18 Kg/cm² INCREMENT.



22.1% Ca - 77.9% Na CLAY
DIAL READING - TIME CURVE
0.60 - 1.18 kg/cm² INCREMENT



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